UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
Region 8
Albuquerque, New Mexico

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EROSION OF STREAM BANKS, ITS PREVENTION AND CORRECTION

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Regional Bulletin No. 78
Engineering Series No. 6
Forestry Series No. 14
April 1, 1942

TABLE OF CONTENTS

INTRODUCTION

Channel erosion in the Southwest Region is recognized as a very important part of the broad problem of erosion. Although a relatively smaller part of the Soil Conservation Service's program to date has been directed toward its correction as compared to the correction of sheet and gully erosion on the watershed, it has probably been due, not to a lack of appreciation of its importance, but rather to difficulties of economic justification and to lack of standardization of professional practices for its solution.

The approach to this problem and the practices proposed in this brief represent the application of recognized technical precepts and usages in combination with numerous lessons learned by trial and error from many developments that have been made throughout the Region.

It seems doubtful if any part of the United States presents greater difficulties to a feasible solution of the problem of channel erosion, or exhibits a greater need for protective measures, than the Southwest. It has been estimated that there are more than 1000 miles of stream banks in Region 8 where stabilization is needed and, in part, can be justified. The reasons for difficulties center around the sparsity and character of rainfall and the consequent effects upon vegetative growth, erodibility of soil, and variability and intensity of stream flow. A few streams are perennial, many are intermittent or ephemeral, a great many are continuously dry except for short periods of the year, some flowing only a few days. It happens also that the locations of nearly all of the agricultural developments and consequent residential and industrial concentrations occur on alluvial valleys or bottom lands. This is because these lands depend upon irrigation and also because very fertile soil is to be found there.

Before human occupation and residence took place in alluvial valleys the indigenous vegetation on the watersheds controlled the run-off of the more moderate flows. In some valleys this cover provided a non-erodible surface for existing stream flow without scouring a channel, such as in the case of the San Simon (Arizona) and Rio Puerco (New Mexico) valleys and many of smaller size. Some stabilization of banks was developed by tree or shrub growth, especially where the stream flow was perennial, or nearly so. With the progress of time an erosional cycle on watersheds developed due to grass cover depletion, and stream flow increases started a cycle of channel erosion and enlargement. In nearly all cases where this erosion has been very rapid, it has been characterized by the process of meandering. Along many channels climatic and soil conditions and stream flow characteristics have not been suitable for establishment of a voluntary tree or shrub growth. On some channels, however, the existing conditions, which generally do not include excessive gradients and consequent excessive velocities, are often suitable for this growth when it is planted under control measures such as are outlined in this brief. The limits of maximum velocities where vegetative measures are practical are about 10 to 12 feet per second average for the total cross

sections, or 15 to 20 feet per second for the greatest velocity at any point in the cross section.

The extent to which channel erosion has proceeded or may proceed in alluvial valleys depends upon the particular factors affecting each particular valley. Already in some valleys the alluvial deposits of fertile soil of which they were composed have been completely lost by erosion, and the entire width of valley has become a sand wash. There also are other valleys now in early stages of the erosion cycle that are doomed to destruction for agricultural purposes unless control measures are undertaken.

Much has been expressed as to the feasibility of channel stabilization. Doubts for many cases are believed well founded, not so much from technical limitations as economic ones. Whether or not channel stabilization is justified will depend entirely upon the economic assets and potentialities of each prospective project in relation to the cost of stabilizing measures. Where no agricultural developments or potentialities exist, the justifying factors for stabilization are usually found in the extent and rate of delivery of a potential silt source as it affects reservoir storage or other developments further downstream.

Regardless of whether a channel stabilization project pertains to a large or small valley, although especially important in small agricultural valleys, it will be necessary in nearly all cases to use great care in designing and planning to develop practices at a cost which can be justified by a fair economic analysis. It has been learned by experience throughout Region 8 that undoubtedly the cheapest successful practices embody a combination of tree and other vegetative growth with engineering structures. With economy of costs to be considered, structural work should be proposed only where there is a need to protect and foster vegetative growth, or to take the place of vegetative measures where the latter will not serve. Both types of work will need maintenance and follow-up, and to be successful, both original development and maintenance must be part of a comprehensive plan. In connection with the original design and plan, it is especially desirable that the native materials of trees, timbers, brush, and rock which can be procured locally be used as much as possible, that a low limit be placed on use of expensive materials which must be purchased, and that plans be adaptable to the capabilities of local labor and equipment. In short, it is essential that the type of protective work adopted be within the means and the ability of the cooperators or landowners to create and maintain.

In regard to planning, it should be further recognized that the work of creating and maintaining a stable channel may represent in many cases only a part of the problem of valley stabilization and that in itself it does not provide protection to the flood plain and valley from channel overflow. It should be further recognized that all problems of channel stabilization are interrelated with tributary watershed treatment. Furthermore, in certain problem cases a modification of stream flow and reduction of its sediment content by watershed treatment will be necessary before channel and valley stabilization can be practicable or justifiable.

STATEMENT OF PROBLEM

It is quite obvious that the principal objectives of channel stabilization work will be the fixation of a channel bank to prevent the removal and destruction of the alluvial soil of the valley floor behind it and the preservation of the improvements thereon. This stabilization serves for one erosion operation only -- bank cutting. It is a matter of observation that bank cutting alone is responsible for the greater part of flood damages in agricultural valleys, at least from the flood flows of average years, as contrasted to flood flows of rarer frequency. It is during the periods of long and intense floods that the greatest danger exists for the formation somewhere on the valley floor of a new channel. For this reason a channel stabilization program should take into consideration this possibility and should include protective measures to be carried out on the flood plain to minimize, if not entirely eliminate, the serious consequences from this source.

Three different types of study are necessary in order to properly evaluate the extent of a channel stabilization problem, and to judge its feasibility.

1. One of these is an economic analysis which should take into account the record of damages incurred, both seasonal crop or improvement losses, and permanent soil destruction. It should distinguish between losses that may be prevented by the proposed protective measures and those that cannot be prevented; it should also attempt to estimate probable future rate of losses as distinguished from rate of past losses. The degree of refinement of the system of analysis which may be justified will depend upon the size and cost of the project. On large projects the system employed should not vary greatly from that employed by the Flood Control Section of the Soil Conservation Service. This analysis will forestall further consideration of proposals where benefits are obviously out of line with cost estimates.

2. The determination of the technical feasibility of a project and construction planning require a knowledge of the physical conditions of channel, valley, and watershed. An examination or survey to determine these conditions should describe the following physical features: valley and watershed topography (including slopes, elevations, and vegetative cover), soil (extent, quality, and characteristics), and any geologic features of influence. Factors of present and past land use and ownership boundaries are valuable supplements to existing physical conditions and may be secured at time of physical surveys. In this connection, any existing maps will be of value. Aerial photographs are probably the most valuable.

A special feature of the survey will contain data pertinent to the stream channel itself: cross-sections, gradient, channel bank slopes and alignment, character of material in banks, and character and extent of trees and other protective vegetation that are to be found on stretches of

existing banks or on the flood plain and valley floor near by. Observations of vegetative growth on channel banks should be made with regard to value for incorporation into a comprehensive project plan. Observations of trees and brush (shrubs) in the valley and elsewhere should be made for consideration as a source of structural material and of planting stock which may be usable in a plan of projected measures. In this regard, good management practices should also be considered as the use of certain species may be helpful to the stand of trees while the cutting of others may not be advisable. The location of trees especially should be noted as to whether or not they may become favorable or unfavorable influences when large floods occur.

3. The third study to determine basic data needed in planning is a hydrologic study of the watershed. This study should take into consideration all existing run-off and rainfall data, including local reports for small or isolated watersheds. It should also include theoretical determinations of stream flow expectancy made by standard methods based upon the area of watershed and the factual assumptions indicated from available data. The character of low-water flow should be determined, as this information is essential to tree and other vegetative growth planting. A knowledge of flood characteristics and maximum flood-peak flow expectancies is essential for the planning of channel size and alignment. Estimates of various flood flow factors are needed. These include peak flows for various time intervals - 1 year, 25 years, and 100 years; also volumes of run-offs for corresponding floods and annual averages. Information obtained from local sources is often of value, but should be carefully weighed for accuracy.

The following are some of the outstanding factors of the problem which must be taken into consideration in adopting and carrying out a plan of protective measures:

1. Consideration of the hydraulic and mechanical principles that enter into the operations of stream flow, erosion, and sedimentation, and that contribute to the problem or its solution.

These basic factors are discussed hereafter under a separate chapter heading.

2. Adoption of a satisfactory channel capacity.

Experience has shown that only short sections of channel usually exist where no alteration of channel size is desirable, or where protective measures should not involve either enlargement or reduction of channel size. In adopting a channel capacity it is important that the portion of the discharge of flood flows which is carried over the flood plain, as distinguished from that in the channel, is not of such depth, or the velocity so great, that serious damage by scour will occur. With this in mind one must take into consideration the factors of flow expectancy and the width, depth, and cover of the flood plain. An estimate of flood plain flow will be influenced by the probable increased depth during flood flows

in the adopted channel. It is believed that the best approach to adopting a normal channel capacity must be determined individually for each channel under consideration. For determining a suitable width of channel a practical guide to use is the width of a stabilized section within the reach being planned, as such a section represents a living measure of past and present conditions. It is apparent that it may often be desirable to determine what channel capacity will produce the occurrence of occasional moderate flood plain overflows. Such overflow may perform the functions of land leveling and upbuilding of low areas through sediment deposits, also natural irrigation and fertilization. The area occupied by a channel bed should be free of vegetation as it can serve no useful purpose other than the conveyance of stream flow; the flood plain, on the other hand, may be useful as a vegetative habitat supporting a grass cover, timber, or woodlot which has human and wildlife value. Where vegetative protection is to be established, the channel should be sufficiently narrow to afford moisture by constant or frequent contact with stream flow at the toes of both channel banks. There are some examples in this Region where the existing channel width is so great that willow plantings on one bank died from lack of moisture and infrequent contact with stream flow. The width of channel also has considerable bearing upon maintenance as the cost of maintaining an open channel wider than one which the river itself will keep relatively clear is apt to be prohibitive. If too wide a channel is established, it will be difficult and costly to keep shrubs and trees from becoming established within portions of the channel. This would encourage meandering and tend to increase bank cutting.

Some channels in Region 8 of satisfactory size have a capacity approximating, or slightly less than, that of the average annual flood flow peak.

3. Adoption of a satisfactory channel alignment.

Any comprehensive plan for channel stabilization should take into consideration possible advantages or disadvantages from improvement of alignment. Where channel bank stabilization is a problem that warrants attention, the process of meandering has nearly always proceeded to a point where the alignment (as well as size of channel) is not suitable for practical stabilization of the channel banks in their existing location. The sharper the curvature of a channel bank, the more difficult is the problem of providing a stabilizing medium. There occurs a degree of bank alignment for each channel at which vegetative cover can not be maintained even though temporary structural measures have been provided for its establishment. Where such degree of curvature exists, stabilization may be effected only by expensive structural work. If necessary or desirable, and the cost is justified, satisfactory structural work can be designed for any bank curvature. It is believed, however, that such procedure will rarely be justified in this Region. From the point of view of costs, it is cheaper to establish a new channel bank with a lesser degree of curvature that will permit the maintenance of tree or other vegetative covers. There is no doubt that in a channel plan the straighter the alignment adopted, the more satisfactory will be the performance of vegetative bank

protection and the lower the cost of maintenance. On the other hand, there are a number of factors that will control the extent of change in the channel alignment, such as the added amount and cost of structural work, including channel excavation, and the presence or proximity of improved property involving loss or hazard. The problem of alignment correction involves numerous factors that require integration to arrive at a solution. The correctness of the recommendation will depend largely upon the judgment and experience of the technicians making the plan.

4. Protection of vegetative plantings.

This is a very important point in work planning and often is not appreciated or is deliberately neglected. Tree growth, although strong and sturdy when it has become well established and has gained size, is very delicate when young, and survival at that time is often very difficult. Young tree plants are succulent, and consequently are a chosen browse of stock; this is especially true of certain species adopted for bank protection. It is, therefore, absolutely essential that provision be made to exclude all stock from areas of new plantings. The surest way is by fencing the areas where planting has been undertaken.

5. Determination of channel bed variations and seasonal trend as to aggradation or degradation.

This is a complex factor related to the processes of erosion, sedimentation, and character of stream flow. A fair appraisal of the condition can be made from local observation and reports, if better data are not available. In planning and designing, this factor is very important. All streams not on a solid bed develop scour during floods and redeposition as the flows recede. The amount of scour varies with the velocity, duration of flow, and size of bed material. The lowering of bed level at the maximum point during excessive and prolonged floods ranges from 50 percent in some streams to 500 percent in others in terms of the rise in surface water level. It is necessary to determine and consider this factor for any channel bank work under consideration. In straight channel sections securing takes place near the center of channel; in curved sections it is close to the outside of channel. Any structural work recommended for bank protection must provide for this possibility in protection of toe or the effectiveness and integrity of the structure will be lost.

6. Availability of native materials for use in structures and for planting stock.

A survey of the character, extent, and location of growing trees and available rock and gravel is one of the first essentials in making designs and preparing a plan of bank stabilization. Suitable tree planting stock may be found growing in the flood plain near the channel. If planting stock must be transported long distances, the cost of a planting program may be considerably increased. Prevalence and size of planting stock may be the determining factor as to whether large or small cuttings

will be used and the manner of planting. Where large posts are available, the extent of the supply may govern the manner of use, whether for planting only, or in structure and planting combination as in the use of structural members made of willow posts which may take root and grow. The character and prevalence of rock, and whether it is found in loose state or must be quarried, may be deciding factors in the design, extent of use, and cost of structural work. The availability of gravel and sand, in case of absence of rock, and its suitability for concrete may also be factors in planning the type of structural design. Whether a channel stabilization should be started at the upper or the lower end of a valley has been a controversial point. It would seem that the soundest basis for the selection of a point at which to start a job should be the selection of the point where work is most needed, and from this point continue in either or both directions for as long a stretch or range as practicable. Care should be taken that the work at any one location shall not cause damage at points above or below, or that work done in one work season shall not cause damage before work is resumed.

7. Channel bottom stabilization.

This matter is extremely important on all streams. There are two types of problems. The less important is probably that of aggradation where conditions can be improved by the narrowing of channel width, establishment of definite banks, and building up of the flood plain by the natural deposition of sediment. The other type of problem has to do with degrading channels which occur most frequently where stream courses traverse narrow alluvial valleys and empty into parent streams at lower elevations. If the alluvial fill is deep, bed erosion and deepening of the channel becomes a serious problem. An outstanding example of this condition is found in the valley of the Colorado River near Grand Junction, Colorado. The solution of this type of problem calls for channel barriers, or drops, as well as bank stabilization.

STATEMENT OF BASIC PRINCIPLES, BOTH THEORETICAL AND APPLIED, UNDERLYING THE PROBLEM OF BANK PROTECTION AND STABILIZATION PRACTICES

Following is a list of certain pertinent basic principles of hydraulics and mechanics that explain the nature of the problem in question and point out requirements of practical measures recommended. (See accompanying exhibits by Clare R. Van Orman and Lloyd B. Smith.)

1. Stream erosion or scour increases with the square of the velocity.

2. The silt-carrying capacity of a stream (bed load) increases with the 6th power of the velocity.

3. The narrower and deeper a channel, the higher will be the vecolity and consequent erosion (increase of hydraulic radius).

4. The straighter the channel the less will be the bank erosion.

5. Bank erosion will increase with the erodibility of the bank material.

6. Magnitude of forces reacting between flowing water in a curved channel and the restraining bank will vary with the velocity of the current and the degree of curvature of the bend, or angle of approach of current to bank in the event of cross-channel flows.

7. Erosive action taking place around channel bends is helicoidal in nature. A considerable part of the erosive forces, being vertical, are downard, causing the removal of eroded material by undercutting and bank caving.

8. The downward erosive force against a bank is greatly reduced when the water surface overflows the bank.

9. Observation and laboratory experiments have established the fact that the greater part of bank cutting occurs during the period of flood recession. Explanatory factors of this occurrence are: a) this is the period of longest duration and largest volume of flow; b) velocities for same discharge are relatively higher due to greater depth; and c) point of maximum cutting is vertically lowered due to progressive scour of channel bottom.

10. In channel cross sections where alignment is straight, the point of highest velocity occurs near center of width and close to surface of flow, with relatively lower velocities occurring at point of contact with channel banks and bed. Where channel alignment is curved, however, the highest velocity occurs very close to the outer edge of the channel and more nearly at the center of water depth. This low point of application of erosive force explains the greater depth of scour frequently observed near the toe of bank in curved channels, and the increased rapidity of bank caving

11. Channel bends, when left unprotected, tend to move downstream. The high sediment load of the current derived from immoderate local bank cutting along concave banks is deposited in part on nearby convex banks and recessed channel pockets downstream.

12. Constructive work designed and planned to resist channel erosion centers around several functions: a) in the case of impervious works, such as jetties and revetments, either directly against or some distance away from the bank, and plating or close vegetative covering on existing banks, the function is one of complete deflection; b) in the case of pervious structural work or vegetative covering on existing banks, a partial deflection occurs which is sufficient to reduce the potency of the resultant erosion upon unprotected points of the bank; c) in the case of pervious structural work placed at a distance in front of existing bank and along a new line adopted for improved channel alignment, or in the case of tree growth established either in conjunction with the structural work or in

the space between it and the old bank, the functions of moderation of current and deposition of silt behind the structural work are of equal or greater importance than that of partial deflection.

13. For a caving bank, especially when its alignment is on a bend, the key to successful stabilization lies in stabilizing the toe of the bank.

14. In any structural designs for use on curved alignment, it is important to provide horizontal obstruction to resist the downward cutting force of helicoidal currents, as well as vertical obstructions to resist the longitudinal component of velocity.

15. In the case of channel banks on straight alignments, some protection to toe of bank below water surface, as well as to slope of bank above water surface, is generally needed to act as insurance against possible local deflection of current against bank from snags and gravel bars.

16. In the case of impervious structures, greater strength must be provided in their design than for pervious structures because they are exposed to greater forces.

STATEMENT OF ENGINEERING PRACTICES AND DESIGNS

The first step in the procedure of making a plan for stream bank channel stabilization consists of preparing the three surveys: 1) economic, 2) hydrologic, and 3) physical. How extensive or refined these surveys should be may be determined by the extent or importance of the proposed project.

If the analysis indicates the likelihood that a feasible project may be developed, the next step in procedure is the preparation of a comprehensive plan. This includes the following steps:

1. Determination as to what part of the existing channel alignment may be preserved as an adopted channel alignment.

2. Indication of approximate location of stretches of channel where straightening of curved sections or bends is recommended.

3. Determination of width of channel to adopt.

The hydrologic survey, and extent and character of stream channel and flood plain will indicate what channel capacity should be adopted. Survey data will establish the factors of channel gradient, height of banks, area of section, hydraulic radius, and coefficient of friction of stream bends and banks, and make possible the calculation of the width of channel necessary to secure the desired capacity. The part of the total flood flows that can be handled on the flood plain will enter into the determination of channel width.

4. Adoption of degree of curvature.

The physical survey will furnish data on stream bank erodibility. Channel computations will indicate velocity expectancy. The economic survey will establish the cost limits of the proposed project. Using these data as guides together with a knowledge of availability of native material and contingent property losses if a change in channel alignment is made, the planning engineer must decide how great a variation from a straight alignment it is justifiable to allow. A determination on this matter represents an integrated solution of many variables. Each location is a problem in itself. Arbitrary limitations as to degree of curvature adoption for channels in general will not apply to all individual cases. Some of this Service's early experiences in attempting to stabilize channel banks on too sharp curvatures with the consequent failures should be a warning against undue optimism. Any mathematical formula used as a guide to determine a permissible degree of curvature would involve the factors of velocity, stability of stream bank and bottom, and strength of protective work and adequacy of its design. It is quite apparent that success in applying such a formula will depend greatly upon judgment based upon experience. Consequently, provision should be made when major projects are under consideration in the several regional areas for the review of the conclusions by the regional staff.

5. Structure locations.

The extent and character of structural protection will be determined largely by channel alignment curvature, as well as the other factors that entered into curvature determination. The most extensive structural work will be located on the outside of curves. Usually the next most extensive work will be channel excavation. This will include making new channels, either to designed channel capacity or by means of pilot channels that are to be enlarged by natural flood flow. There will be work also on existing channels -- enlargement, and bar and debris removal. Miscellaneous structural work includes special modifications of work mentioned, such as diversion dams and protection to existing public service structures. There are two important factors that may modify alignment location. One of these is the matter of existing bridge and irrigation dam and outlet locations where satisfactory structures exist. The planned alignment must be made to conform. In some valleys an opportunity may exist for improving the irrigation system by improving the types and locations of the diversion dams and outlet structures, or in combining several points of diversion and unifying the canal system. In this case, channel location should take this into consideration. The other factor has to do with the entrance of tributary streams into the main channel. Provision must be made for the break in the main channel bank and in the location of protective structures. Sometimes it will be desirable to carry the stabilization of the main channel bank some distance upstream on the banks of the tributary stream. Where coarse silt deposits are in such amounts as to choke the channel, it may be necessary to carry out measures on the tributaries to retain the sediment within the tributary watershed, or at least retard its outward movement.

6. Structure types and designs.

It has been pointed out that while practically any channel bank, however sharp the curvature, can be successfully stabilized by expensive struc-

tural work of impervious design, it will be a rare occurrence in Region 8 when other than the cheaper types of pervious structures can be justified. Since a foremost object in planning protective work will be the creation of conditions where tree plantings and other vegetative growth, when once established, can perpetuate the original functions of structural work, the design of this structural work need only be sufficient to perform this temporary function. Native wood and timber will be used extensively in this work.

Where existing bank locations are adopted, the banks should be sloped at, or flatter than, the angle of repose of the material. The slopes and the toes of slopes should then be protected by suitable structural work or protective material if their erodibility requires it. This will nearly always be required on good alluvial soil, especially on curved alignments.

Adaptable types of structures may be classified as follows:

a) A "flexible string of trees held by a line of cable" and anchors. This is probably the cheapest structural protection and very efficient, cheapest at least as regards material to be purchased. Its efficiency will increase with the size of the trees; the maximum size will be limited, however, by transportation facilities and by channel width. In streams carrying a heavy debris load, this type of protection, as well as all other types of pervious jetties or revetments, collects much debris which affords a more impervious covering and prolongs the effective life of structural protection. The effect on reduction of channel width should be allowed for in designing channel capacities. This type of work is adaptable for use either on existing banks or along a new alignment in front of the bank. Greatest limitation to this type of work is length of life; the larger the trees, the longer the life. Constant inspection and maintenance is essential. Parts of trees continuously wet or moist will function for a long time. Effectiveness and life are dependent upon strength of cable and anchors. Where old cable is used, allowance should be made for reduced strength. The trees, with all branches left intact, form the largest area of resistance. They should be attached to the main cable line by a small secondary cable at points near the butts, 1/10 to 1/5 of the tree's length. The axis of the trees should take a downstream direction. This type of work is very satisfactory for the protection of the toe of the bank. It can be placed on a dry bed and will settle sufficiently during flood flow. Two types of anchorage provision, or a combination, may be used with this type of structure, namely: one anchor on each end of a long cable with many trees attached along the line. This type is especially suited where the structure location is at a distance in front of the existing bank. Anchorage here may be reinforced by the individual anchors of the cross lines which are attached to the

main cable and extend diagonally to the bank. When this type of work is located directly against the existing bank, numerous short lines of cable with one or more trees may be anchored individually behind the bank. The same principles govern the strength of anchors and cables as for any other type of flexible structures. This type of work will cost from 25¢ up per lineal foot.

b) A modification of type (a) is a flexible mat of brush. It is adaptable as a plating for existing banks, but is not suitable for location on a new line located some distance in front of the old bank. When used as plating, numerous bunches of faggots 1 foot to 2 feet in diameter should be bound together by wire and placed side by side in an upright position on the slope, butts down, and each bunch securely attached by two or more lines of lighter cable to two longitudinal lines of heavier cable. Length of life of a brush mat is short but may be sufficient to establish a vegetative covering.

c) Modifications are adaptable to new channel edge alignment. The simplest might be called "a line of brush faggots anchored and held in place by one row of piling and lines of cable." The channel stabilization job on the Rio Grande near Espanola, New Mexico, employed a great length of this type of structure. Old heavy railroad rails were driven as piles, at intervals varying from 10 feet to 40 feet apart, and acted as anchors for three lines of 3/4-inch cable that crisscrossed above and below faggots of brush 5 to 6 feet in diameter and 12 to 15 feet long. The butt ends of the brush were placed on the river side with the individual pieces of brush and faggots laid transversely to the lines of cable. Timber piling may be used where length of life and required strength permit. Piling must always be driven sufficiently deep for stability during channel scour. The depth of penetration below anticipated bottom of scour should equal 1/3 the length of steel piling and 1/2 the length of wooden piling.

d) Another modification of this type that, like type (c), is suitable to a new alignment consists of two rows of piling placed a few feet apart with small brush placed lengthwise between the two rows with bottom layer in a trench to a depth as close as practicable to lowest level of contemplated scour. Woven wire may be used between piles to support and envelop the brush, or not, depending upon the required life and strength. Length of piling should be the same as for type (c). Stability of this type of structure can be increased by transverse or diagonal ties between tops of piles with 1/4-inch to 1/2-inch cable.

e) One of the most common practices that requires relatively little purchased material and has a very wide adaptability, either for protection of established banks and toes of banks, or for channel edge establishment, is the use of one line of piling with a facing of woven wire. This is the type of structure employed by the Middle Rio Grande Conservancy District. In this instance, as wherever piling is used, its success depends largely upon whether the piles are driven deep enough. In exceptional cases, 25- to 40-foot piles employed on the Rio Grande with 5- to 8-foot projection above low-water stream bed have been washed out during floods. (Local scour of 40 feet maximum was observed in the sandy bed of the Rio Grande during the spring flood of 1941.) Besides depth of penetration, the buoyancy of material is an important factor in the stability of piling. Where wooden piles are used, life of structure may be increased by creosoting. Old railroad rails of proper weight and length are undoubtedly the most satisfactory type of piling for general use. They are relatively cheap, heavy, and long-lived. Precast concrete piling ranks next in weight and length of life but is costly. Timber piling, if driven sufficiently deep, will usually serve the temporary purpose of protecting a tree growth habitat required on Soil Conservation Service projects. The question as to whether woven wire is placed on inside or outside of posts is controversial. Where deep channel scour was expected on the Rio Grande, the woven wire facing was attached to the river side of piles. Where the woven wire facing came in contact with the stream bed, it was extended horizontally on the stream bed for a distance equal to the anticipated depth of scour; at the extreme edge of the wire concrete weights were attached at intervals to settle the wire into a vertical position during scouring stream flows. A considerable strengthening of this type of work may be obtained by fastening the top of each pile to a horizontal cable. Where this line of pile revetment is placed directly against a bank, a continuous wall of brush laid lengthwise will increase resistance to bank erosion.

f) A modification of type (e) is two rows of piles with a sausage of loose rock between them. This is an expensive type of construction, ranging from $3 up per lineal foot, that has been used extensively in Region 8. It is almost impervious in nature. Its essential advantage over cheaper impervious types is the positive protection to valuable property, such as improvements and urban developments, or to locations where subsequent vegetative protection is not practical. Good design should provide for penetration of pile to at least 1/4 length below anticipated depth of scour. A trench to at least 1/2, preferably more, of scour depth should be made between the two rows as foundation for woven wire

basket of rocks. The wire envelope need not cover top of loose rock wall if no settlement is expected. If settlement occurs, a woven wire covering placed during construction may subsequently be raised vertically and attached to the projecting piling, and the basket refilled to the top of the wire. This type of structure may be strengthened by attaching each river side post, at the top, to a line of heavy cable and tying the inner row of piles to the outer row by transverse or diagonal ties of lighter cable, 1/3-inch to 1/2-inch. When available, old railroad rails are superior to timber for piling.

g) A modification of type (f) of cheaper cost ($1 to $2 per lineal foot) consists of one row of piling with a facing of wire mesh, the lower edge of which is carried horizontally under a wall of loose rock. This type has been used extensively by the New Mexico Highway Department for wing embankments on approaches to bridges, and by the Soil Conservation Service near Santa Fe at the edges of gravel washes. When the stream bed is subject to very little scour, hand-dug holes may suffice, and posts instead of piling may be used. In this case, posts should be placed on an upward, bankward slope of 1/4:1 and the rock placed behind them in contact with the wire mesh which is attached on the bank side of the posts. The back face of the rock should be vertical. Against this back face of rock will be placed an earth fill connection with existing bank or with an earth dyke where no bank exists. The stability of this type of work will depend largely upon adopted depth of foundation for rock wall as compared to flood scour depth.

h) A common type of structural work for bank building and bank protection consists of a series of floating or semi-floating obstructions held in location by one or more lines of cable. Many solid geometric figures are adaptable for this purpose, some of which have been patented. The efficiency of any such obstruction may be measured by its over-all area and uniformity of size and spacing of open spaces or interstices. They are adaptable for use on either established banks or for new channel edge alignment. The Soil Conservation Service has made installations of the tetrahedron form constructed of old railroad rail. To increase the area of resistance over that afforded by the six members, wire in both single lines and mesh has been attached to the several members as a surface envelope. Further efficiency may be secured by placing a continuous line of wire mesh from one tetrahedron to another. Tetrahedrons made of old railroad rails will settle to nearly the depth of maximum scour. The amount of settlement may be reduced by a base support; the more impervious this is, the less will be the settlement. Instances have been observed where trees were planted within the tetrahedrons and thereby created a foundation which

reduced settlement. The adopted design size of tetrahedrons will be determined by the probable settlement and desired height of bank deposit. Deposition occurs to a level slightly lower than the top of pervious structures.

A line of small tetrahedrons will form an excellent toe-of-bank stabilization. Since a line of trees and cable will serve about as well, however, and, where moisture is present, have almost equal life, the selection of this type should be very infrequent. A tetrahedron line is well adapted to use for establishment of new channel edge when material or equipment for other types of work is not available. Proper allowance for cable and anchorage strength is essential. Where degree of settlement is uncertain, secondary protection against high velocities in the channel strip between structural line and old bank is important. The tetrahedron design is suitable to any available material of sufficient strength, such as old car frames, or timber. A floating timber structure has the advantage of greater buoyancy, and consequently less settlement, though shorter life.

i) One of the simplest, most widely used, and most satisfactory bank protection practice consists of a facing of loose rock, either dumped in place on a rough slope or hand-placed on bank slope as riprap. Rock dumped in place is commonly used by most railroads. The latter method is not adaptable unless toe of slope is stabilized; stability increases with flatness of slope, 2:1 being favored as the minimum. Where loose rock is dumped in place to protect existing surface, or establish a toe, its stability will increase with the size of rock. Its use is governed by its availability and that of equipment to handle it. A very common modification of this type of work is the rock sausage or mat. This consists of a quantity of small boulders encased in an envelope or cover of woven wire. Other types of structural work of higher efficiency and greater cost which are elaborations upon loose rock riprap are grouted rock riprap, selected rock or rubble riprap, sacks of concrete, and concrete slope lining - both reinforced with steel and unreinforced.

j) A common, satisfactory type of installation not used extensively by the Soil Conservation Service in this Region is crib work used as revetment or jetty. Timber, precast concrete or steel constitute the encompassing walls of a depository for loose rock. When used to protect an existing bank or act as a retaining wall, one face is used with transverse members extending into bank for anchorage. This type of construction is also adapted to use in shallow channels as intermediate anchors for cable and tree lines. When so used, diagonal encircling ties of cable are essen-

tial to hold the crib together under conditions of unequal settlement. This use as anchors has been made by the Soil Conservation Service in the Eastern Utah Area.

k) A very common type of bank stabilization is the spur jetty. This type is distinctive in its shape and location rather than in its manner of construction, and may be constructed after the manner of any of the above mentioned types. In application, a spur jetty extends into the channel from the bank edge where it must be securely tied against bank-cutting. In theory the channel end of the spur acts as a point in a new alignment. Many shapes of jetties, and varied directional forms of face in relation to direction of channel current, have been employed. Those with an upstream face curved horizontally with the direction of current possess the soundest design. (See exhibit, Orman - Fig. 8.) The principal function of a jetty is to deflect current to an adopted channel line; the secondary or incidental function is the creation of a quiescent pool behind the jetty if it is an impervious jetty, or an area of reduced velocity if a pervious jetty, thereby creating an area of deposition or of minimum scour. Thus a habitat for tree growth and vegetative protection is provided the same as by continuous or training jetties. Where the newly adopted alignment of channel edge is quite long, several jetties will be needed. As a supplement to spur jetties where the alignment is on a sharp bend, it is recommended that a light line of continuous pervious jetty connecting the ends of the spur jetties be added to establish more uniformly the new line of bank.

l) In conjunction with all continuous jetties of considerable length that are located at a distance from existing bank, secondary cross-jetties are necessary to prevent concentration of current and make possible uniform deposition. Their location should be either at right angles to the jetty line or at a slightly downstream angle to the channel current. It is apparent that only the cheapest types of work are needed and should be employed.

m) Dykes or levee designs are often a logical and desirable structure type connected with bank stabilization. Standard specifications used for dams of like size should be employed for dykes and levees. Protection of the face of dykes and levees is equally important as protection for the regular channel banks.

n) In this list of structural types it has been pointed out that the lowest-cost work which will accomplish the desired results is essential to justification. This does not preclude the design and construction, however, of more permanent types of structures when needed. There would

include numerous designs in rubble masonry, concrete, structural steel, and steel sheet piling in critical cases of last resort, if ever justified.

Where stream flow is diverted from an old channel to a new one, the diversion structure becomes the same type as would be adopted for any other location as a jetty or revetment.

o) In connection with a complete new channel location, as where a straight alignment is substituted for one or more bends, the construction operation of excavation may be simplified, and the expense greatly reduced, by the mechanical excavation of a channel of only part of the designed capacity instead of the full designed capacity. Such a channel is commonly spoken of as a pilot channel. When its location is in alluvium or loose, redeposited sand and small gravel, velocities of flood flows through channel are considerably higher than in the channel sections at approach or outlet, because of the local increase of gradient and larger hydraulic radius that comes from constriction of flow into a relatively narrow, deep stream. As a consequence of this fact, rapid scour takes place, both of banks and bottom, and a single small flood will often enlarge the pilot channel size to that of the designed size. In this cleaning-out process the local increased sediment load of the flowing stream is carried on through the full channel length. A part of it is temporarily deposited in larger-than-average channel sections downstream from the pilot section, on channel bottom near inside of bends, and on channel sections of flatter-than-average gradients. This natural process of channel capacity and gradient equalization automatically adjusts itself during a prolonged flow or several small floods.

As soon as natural developments result in new channel bank locations on approximately the adopted lines of a designed location, the same stabilization practices as for the existing banks of a fixed channel, or for minor bank line correction, must be carried out.

Experience has shown that where jetty-type structures of average strength are employed for diversion of flow to a pilot channel, successful enlargement may be expected with the adoption for pilot channel of as little as 20 to 25 percent of the normal channel. Smaller sizes have been successfully used under lucky conditions of flow, as for example, the occurrence of early small flow increases before the occurrence of large ones; also, where the diversion structures were sufficiently strong and the flood plain and out-of-channel conditions were suitable for standing up under the more destructive flow increases for the longer time interval needed to enlarge the pilot capacity. On the other

hand, there have been several examples of failures or serious damage to property in the early work carried out by the Soil Conservation Service due to not providing pilot channels of sufficient size, depth, or gradient, or entrance mouth.

A well-designed pilot channel should provide a large bell-shaped entrance. It is recommended that the entrance width be two to three times that of the rest of the pilot channel cross-section and the depth be 150 to 200 percent of the rest. The length should be at least equal to the entrance width, preferably longer. In alignment, a pilot channel section should be straight and its location should be at the center line of the designed plan.

Since a pilot channel job is a part of a plan to improve a channel alignment, it is assumed that the angle of curvature of channel at entrance and outlet will conform to standards of moderate curvature. The structure that crosses an existing channel to lead the stream flow into a new alignment acts first as a diversion dam. After deposition has filled the abandoned old section with sediment, the location of the old channel becomes a flood plain and the diversion dam becomes a revetment, or continuous jetty, forming the edge of the new channel. It is evident, therefore, that the alignment of the diversion dam shall conform to the same standards of alignment as adopted for establishment of any other stretch of channel edge.

It hardly need be mentioned that in the actual construction operation of new channel formation, the first step to be taken is that of clearing the right-of-way of all trees, brush, and large debris. There are cases in Soil Conservation Service experience where failure to do this caused the deflection of the channel into an undesirable course, thereby damaging property which the work was planned to protect.

p) Improvement of the flood plain has been mentioned as a problem of flood protection that is closely associated with bank protection. The flood plain is called upon periodically to carry the surplus of flood flows which the channel cannot carry. It is apparent that the more uniform the topography and cover on the flood plain, the more uniform will be the velocity and the less the danger from scour. In the management of flood plain lands this factor should be considered. Economic factors as well as physical factors will determine the land use. Cultivated lands are usually quite uniform but are subject to scour due to their lack of permanent cover. Dykes, levees, and barrier hedge plantings may be needed to prevent scour. Grass makes a very desirable crop on land subject to flooding where growth conditions are such

that a uniform thick growth or sod can be maintained. Where such conditions exist the land will usually be used for grazing. Occasionally on flood plains where adjoining channel banks are of moderate height, or where adjacent valley bottoms are irrigated, the ground water table is close enough to the surface of the flood plain to produce a fine dense grass mat. Normally, however, irrigation of the pasture will be required if a satisfactory grass stand is to be secured.

Some areas are suitable for pasture but need leveling so that they can be irrigated. They may be leveled with equipment. A practical expedient to obtain the benefits of leveling at a relatively small cost is found in a process of natural leveling by sedimentation. This employs the use of low, transverse, level, broad base terraces placed at frequent intervals throughout the length of the flood plain, or by substituting, where incipient channels exist, the use of continuous lines of low rock or brush terrace percolators or a combination of them. The development of this practice, as modified by inclusion of occasional large transverse interception dikes, is presented in the brief entitled "Flood Protection in Narrow Valleys" by William B. Wroth, Soil Conservation Service, which is included in this bulletin as an exhibit.

On portions of the flood plain which will not be used for grass pasture and which is not too dry for woody plants, trees and shrubs will normally be found. Where a cover of this type exists, the unevenness of the terrain and the unevenness of the vegetation permit the formation of numerous channels of various sizes. When flood plain overflow takes place, the velocities in the channels that traverse the flood plain are high; consequently these channels seldom experience natural filling with sediment. Where this condition exists, a systematic installation of channel plugs and planting will tend to fill the channels with sediment and level the flood plain. The planting and management of trees and shrubs should aim to provide a uniform dense growth of a character which will cause uniform deposition during flood flows. The flood plain forest may be a source of fuel and fence posts but should not be used for grazing. For best results the trees should extend from the channel edge to the outer edge of land subject to overflow or be connected to flood plain protection designed to prevent scour on pasture and cultivated fields.

VEGETATIVE MEASURES.

It has been pointed out that in planning a project of channel stabilization one of the chief aims should be control by use of vegetation wher-

ever possible. The objective is the establishment and maintenance of a protective vegetative cover on existing banks, or banks created on adopted alignments, and on flood plain areas. The reasons for this preference are that where conditions of growth are suitable the cost of this type of stabilization is cheaper than that by any other measures -- both first cost and maintenance, and because it is a type of work that can be carried out by the local people.

Proof of the success of vegetative measures is found throughout the Region in stabilized banks and channel sections where the only stabilizing measures consist of the voluntary growth of trees, shrubs and grasses along the banks. A few examples exist where old residents have established and maintained a stable channel bank over a long period by planting and maintaining a suitable tree growth. The Soil Conservation Service has carried out a number of projects in various parts of the Region using trees and shrubs. Results of this work have not always been successful but it has demonstrated the suitability of the method and provided a proving ground that has demonstrated requirements and limitations of adaptability and use that are of especial value for future planning.

In order to establish and maintain suitable vegetation, whether on channel banks or flood plain, a suitable habitat must exist or be provided. This includes suitable soil and moisture, and in the case of establishing new vegetation, protection against the erosive action of stream flow. Structural work, such as tree and cable revetment or other mechanical measures designed to correct alignment, stop further cutting and protect new plantings, will be involved in most cases. This phase of control has been discussed above. To provide a suitable soil habitat, streambanks must be frequently built up by the process of sedimentation before the planting operation can be undertaken, thus requiring delayed planting. This condition may occur where a new channel alignment has been adopted on a location that is now stream bed and is either covered with water or too wet to plant, or it may occur where bank or bed material is too gravelly to be suitable for plant growth.

The matter of securing sufficient moisture for the growth of planting stock is often the most difficult requirement to satisfy. In the Southwest moisture conditions as they apply to rainfall, stream flow and groundwater are frequently such that no tree or shrub growth suitable for bank protection could be established.

Several of the large channels are found in areas of extremely low rainfall. These channels are usually traversed by streams of almost continuous or frequent flows receiving their major run-off from less arid areas. Where these channels traverse irrigated areas, the artificial application of water to the valley alluvium may produce a fairly high groundwater plane. By providing a suitable channel or by other arrangements sufficient moisture can often be provided, making the use of vegetation possible in these valleys of low rainfall. It is in such alluvial valleys also where some of the greatest need for bank protection exists.

In making a plan for vegetative control the location or design of plantings is of first importance. When this has been determined selection of species, type of stock, whether cuttings or transplants, and method of planting are determined. In this determination the factors of site, such as soil and moisture conditions, character of stream flow and other factors having a bearing on the control plan are considered.

In general, vegetative control will consist of a continuous tree and shrub border along both sides of the stream placed to hold the channel in a controlled location and to prevent erosion or cutting of the banks. As success of protection on the banks depends upon, among other things, the prevention of channel formation back of the protected channel edge, it will be necessary to tie in the stream edge planting to control measures where required on the flood plain. A system of cross jetties and barrier hedges across low and bare spots will assist in the prevent of erosion on the flood plain during flood flows.

While the various types of plantings are all tied together in one plan they might be divided into two general groups on the basis of location and purpose as follows:

1. Parallel strips on each side of the stream. These strips should be along the stream starting at low water level along planned channel edge and extend some distance onto the valley floor beyond the top of bank or, in the case of high valleys, extend up the bank high enough to prevent bank erosion during floods. The width of the vegetated strip along each bank required for adequate protection will vary according to the size of stream and the topography of the area through which the stream flows. Usually examples of controlled banks can be found which will indicate what is required. On most streams a minimum of 20 to 30 feet of width is required, although 10 feet may be adequate on some of the smaller streams. Plantings should be continuous. Revetments planned for use with vegetation should either be placed to leave a planting site behind them or be of such a nature that plantings can be made down through them. Plantings should be extended as close to the back side of stream edge revetments as possible to prevent any current of a scouring nature behind the structure. The streambank vegetation must be effectively tied into protective measures on the flood plain to prevent new channels forming during floods.

2. Flood plain planting. This type of planting is made to prevent erosion on the flood plain behind the bank protection proper and also in some cases to cause deposition. For discussion purposes flood plain planting is further divided into barrier hedges and block or mass plantings.

The barrier hedges consist of strips of shrubs and trees several feet in width located across the valley floor at approximate right angles to the channel course. These strips or hedges should be located as much as possible along property or field boundaries. They are especially valuable where the valley floor is of low elevation compared to the stream channel, is cultivated, and is subject to flood overflow. Their function is twofold: to act as a barrier lessening the hazard of new channel formation and to retard

flow, thus reducing velocity and accelerating deposition. Barrier hedge plantings must be correlated directly with the farm and river protection plan. Best results will be obtained if the barrier hedges extend from river bank or bottom vegetation to a level higher than the expected flood height.

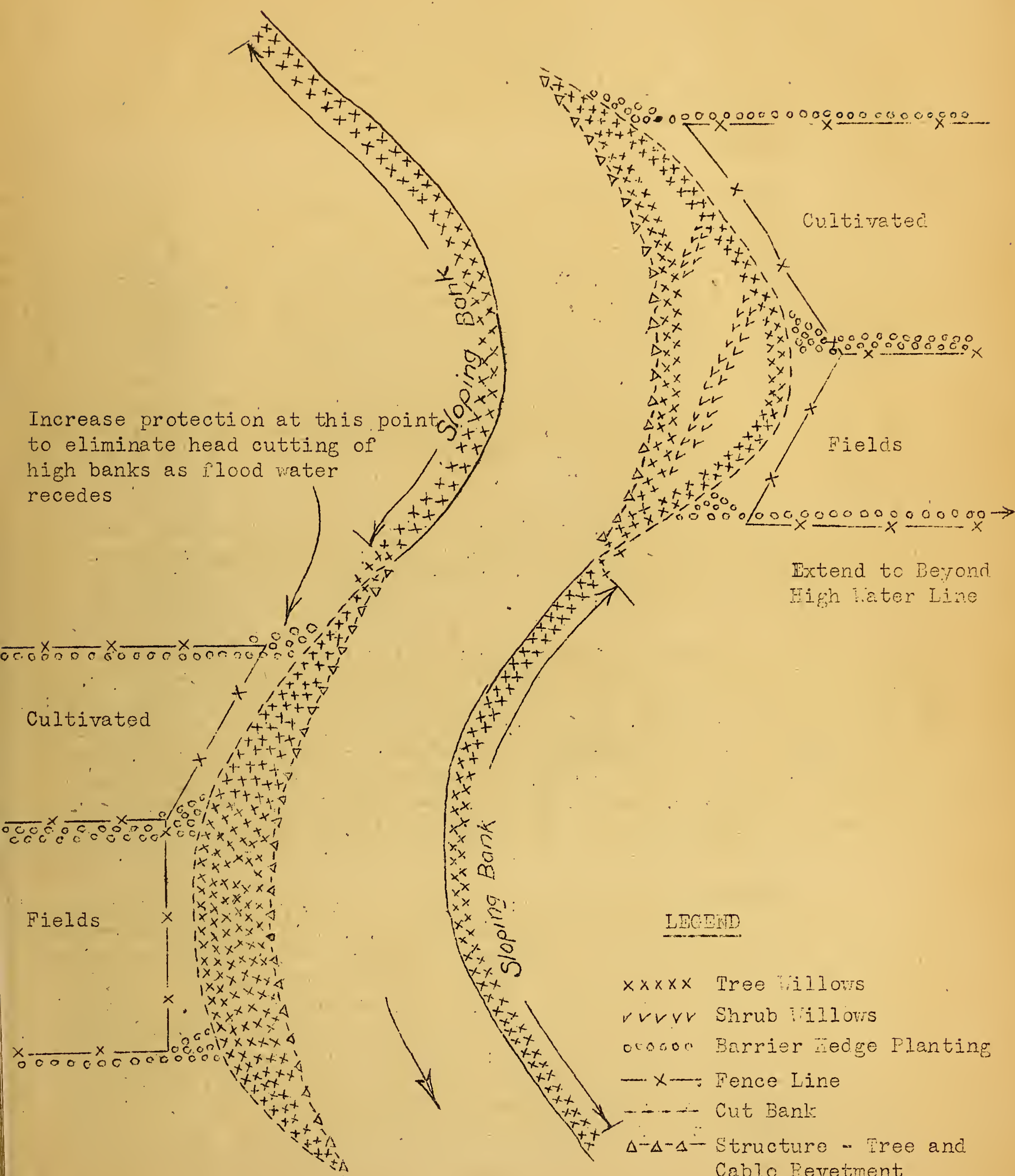
Mass of block plantings are made in locations where it is desired to accelerate deposition and to develop a flood plain cover suitable for prevention of channel formation. Where an extensive meandering of the channel course has taken place in its previous history, abandoned channels as well as new secondary channels often occur which it is desirable to have filled by sedimentation during flood flows that exceed the capacity of the adopted channel. In connection with barriers massed plantings of suitable tree and shrub species are especially valuable for this purpose.

Success of planting will depend upon the techniques employed. To be effective vegetation must start low on the bank because when located only on the top of a high bank and not on the bottom and sides, the vegetation will not prevent side cutting as the bank is undercut during any flow in which the water reaches the toe of bank.

On larger streams tree willows are best to use as edge plantings and also back against cut banks. Their root system is probably the best adapted to resist bank cutting by water flows. They are better able to withstand direct stream action than are shrub willows where heavy flows are periodically expected. In the southern areas Dudley willow is the best tree willow to use while fragile or crack willow are best adapted in the colder portions of the Region. Top growth should be kept fairly dense by periodical cutting back rather than permitting trees to become large and mature. Shrub willow, while not as deep-rooted, will give good results where pressure is not excessive, provided a dense and continuous growth is maintained. Other tree species able to withstand silting may be used for desilting purposes back of the edge plantings. Russian olive is a good species to use for this purpose. It will tolerate considerable alkali which is often a factor in the Southwest. Mass planting on the flood plain may be of any suitable species and, in addition to their protective function, may produce fuel, fence post or other secondary products. Wildlife conditions may be improved in all types of planting. Untried species should be planted on a test basis, and the use of larger plantings should be confined to places where conditions are known to be favorable for their continued success.

In barrier hedges low trees or shrubs are most suitable such as Russian olive, wild plum and, in the southern part of the Region, pomegranate. Any low, dense growing species adapted to the site may be used. Selection of dual purpose species according to the landowner's wishes are usually possible. Species that will not compete unduly with farm crops should be selected. Normally, barrier hedge plantings will have to be irrigated. Barrier hedges may be used alone or with brush barriers or dikes according to the needs of each site. The diagram on the following page shows some planting arrangements including barrier hedges.

STREAM SECTION SHOWING BANK PROTECTION
AND BARRIER - HEDGE PLANTINGS



Spacing on both streambank and barrier hedge planting should be close enough to give early protection as time is an important factor in river control work. Tree willows having fast growing qualities may be planted 4 to 6 feet apart in the row with staggered spacing so that the second row will block the openings between trees of the first row. Rows should not be continuous or of a nature to permit flow lines between the rows in either direction. Shrub willow may be planted as close as 2 to 4 feet apart along the stream front where their use is advisable. Back of the stream edge planting, the spacing may be wider, depending on moisture conditions and species used. Barrier plantings of shrubs should be made on a 3- to 4-foot spacing, depending on the shrub species used. It is important not to allow gaps which would permit channeling.

In planting for streambank protection, cuttings are usually used. Use cuttings from 1 or 2-year old stock or larger material where past use has shown successful results. For establishing plantings on sites unfavorable for cuttings, rooted material should be made available. Cuttings may be planted vertical, angular or horizontal according to conditions on the planting site. The base of vertical and angular cuttings should reach permanent moisture, and therefore, the length of cutting depends upon planting site conditions. If permanent moisture is available near the surface, a cutting 1 foot in length may be satisfactory. In other cases a 5- or 6-foot cutting may be needed, especially with tree willows where deep silting will occur after planting. Willow roots do not ordinarily grow more than 5 to 6 feet below ground surface.

In general, cuttings should not extend more than 3 or 4 inches above the ground unless planted where heavy silting is expected. Cuttings of small diameter should be planted so that not more than 1 or 2 inches appears above the ground surface.

Angular cuttings are used for planting sloping banks. The method of planting vertical and angular cuttings varies considerably. In some places the cuttings can be pushed into the ground to the desired depth. With cuttings of larger diameter, holes may be made with a shovel or post hole digger. Under good soil conditions free of hard material, cuttings may be driven into the ground. A pointed crowbar may be used to make a hole into which the cutting is placed. When angular planting is carried out, a trench may be dug in which to place cuttings. In some cases because of flood danger it is advisable to anchor the cutting into the bank.

In horizontal planting, the cuttings are placed in a shallow trench or may be pressed into boggy ground, leaving the upper portion exposed. They may be anchored with wire butterfly knots. Horizontal planting of cuttings has been used successfully where planting sites are too wet to expect successful results from planting vertical cuttings. Most willow require good soil drainage and will not be successful in stagnant water. The use of horizontal rooted cuttings 3 or 4 feet in length is being tried as test plantings. It is thought that they will have a head start over cuttings and will offer some immediate mechanical protection. When planted, the tops may be cut back but will extend above the ground line of the trench in which

they are planted or anchored.

Willow used as matting on sloped banks and held in place by wire ties or an anchored log constitutes both a mechanical covering and a planting as those portions touching the moist bank take root and form a live willow mat. Vertical cuttings may also be planted through the brush matting to insure plenty of live growth. Where desirable, willow brush may be placed in trenches and partially covered with earth. This latter treatment is especially applicable on small tributary streams.

More experimentation is needed to determine the species of plants most suitable for various stream conditions. This is encouraged, but for general application treatments outlined are based on results of control work done and natural controls observed over the Region.

On small drainageways where flows are infrequent, grass may be used as a stabilizing agent, if conditions are suitable to produce a good grass sod for maintenance of a grassed swale. This will apply where bottom stabilization is such that grass will not be undercut and where moisture conditions are favorable for sod formation on the banks. A field examination of similar sites constitutes the best guide as to whether or not grass will adequately control the erosion on a given channel. Usually on cutting banks of any great consequence, the moisture is either too deep or flood pressure too heavy for control by grass, in which case trees and shrubs are normally used.

Maintenance constitutes a most important feature of streambank and channel stabilization, not only on newly treated areas but on all sections of the stream. This maintenance must cover both the vegetative and mechanical controls and also the open channel.

If a heavy growth can be obtained, it will be effective if in a position where it will not be undercut. Filling in gaps and replanting to form a 100 percent stand is very important and this maintenance of the protective vegetation should in no case be neglected. It should be emphasized that 1 or 2-year old plants cannot be expected to withstand excessive flood pressure. After the third year the planting should become stronger each year until the planting is from 7 to 10 years old when it will probably have reached full value as a protective agent if it has had proper maintenance and protection.

The protection of stream bank vegetation from grazing cannot be too strongly emphasized. Experience on bank control projects has shown that willow planting will not succeed where stock are allowed to browse. Fencing is usually required for protection of the stream bottom vegetation. Protection of existing desirable vegetation will lessen the need for more costly control measures at a later date, and is more effective than attempting revegetation where results may be doubtful.

A changing channel location constitutes a major hazard in maintenance of vegetation. Where the stream is allowed to meander from one side of a natural flood plain to the other, the streambank vegetation, which started on one location, is apt to die from lack of moisture when the stream moves

to a new location. Experience indicates that planting is successful when the channel width is such that the banks are moistened frequently by stream flow throughout the year. Prevention of unregulated meandering also controls the alignment which is an important factor in maintenance of the stream banks. Extreme changes in alignment may subject protective plantings to excessive damage.

To keep an open channel in the desired location, maintenance will be desirable after every flood to removed lodged debris from the channel and to maintain effective control of channel location. Proper management of the stream bottom vegetation will lower the amount of debris available for lodging in channels. Where cut banks are already formed it may be advisable to cut the large trees from a narrow strip along the edge to reduce the hazard from falling trees lodging in the channel and changing the stream course. If not removed, these trees will be undercut and will fall in the stream, possibly causing damage below by lodging and turning the current against the bank. Small islands in the stream channel are a source of the same type of trouble. Usually trees removed can be used to advantage for mechanical protection on cutting curves and as an aid in the establishment of new vegetation.

Repeat pictures and diagrams showing types of control used in various places within the Region are included in the appendix of this bulletin as a further aid to stream stabilization planning.

APPENDIX

Pictures - Utah 601, 601B, 621, 621B, 602, 602B, 602C

The bank protection work illustrated in the pictures listed was the first completed work of this type on the Virgin River. Recent costs of similar work have been 10 to 20 percent lower due to change in materials. It has been found that for most locations smaller cable can be used and cable clamps are not needed. Also, instead of piling used for deadmen on this work, easily available juniper posts could have been used.

In place of equipment which was furnished by the Government, the landowner could have used teams for motive power with a skid pan or similar device to "snake" trees to river bank.

No cost was figured for the large cottonwood trees or the piling used on this work. The trees were furnished by the landowner. The Government furnished the piling which was cut from Government land.

Planning reports for southern Utah counties indicate that the average farmer works an average of only 100 days a year on his farm. This leaves over two-thirds of the year when other than strictly farming work can be accomplished. This spare time could be used profitably in stream bank protection and could be substituted for the Government-furnished labor, as shown above.

This type of protection work lends itself very favorably to a piecemeal method of construction. By this is meant that the cooperator could place one deadman, cut and drag a tree to the site, attach the cable and that portion of the bank would be completed, as far as mechanical construction is concerned. He could then continue on to the next location and repeat the process.

During the late winter and early spring, the landowner could cut and plant necessary willow cuttings behind bank protection. Rooted stock, if desired, could be obtained at very low cost from the State Clarke-McNary Nursery.

The above figures and description indicate that under ideal circumstances a cooperator in this locality could protect his riverside fields with a small amount of cash for cable and his own hours of labor. However, if a group of adjoining landowners could do the work together and have a farm tractor available, the work could be done more efficiently, with little additional cost.

Cost Data - Protection by anchored trees and willow planting.

In the work illustrated by the aforementioned photographs, the follow-

ing costs apply.* This protective work was done as a cooperative job under an agreement between the landowner and the Soil Conservation Service.

Mechanical Protection Work: 2700 lineal feet of stream bank protected by large cottonwood trees cabled to deadmen buried in bank; cabled trees being spaced 30 feet apart with tops extending downstream.

	Cost
Cable -- 7125 ft. 1" cable	$ 260.88
Cable clamps -- 185 clamps	74.00
Gasoline -- 817 gallons @ 20¢	163.40
Large cottonwood trees (no stumpage charged)	0.00
Labor (supervisory and other) -- 8440 hours	2152.56
Piling (used as deadmen) -- 95 10 ft. piles (no stumpage charged)	0.00
Equipment (tractors) -- 270 hours	222.45
Transportation (dump and stake trucks) -- 117 hours	9.85
Total Government cost	2883.14
Cost per lineal foot bank protected	1.07

Vegetative Protection Work: Planting 2700 feet stream bank behind mechanical bank protection using willow post cuttings and rooted trees and shrubs.

Willows (stumpage for 2000 cuttings)	0.00
Labor (supervisory and other) -- 746 hours	291.44
Cost per lineal foot bank protected	0.10

Grand Total Cost:	$3174.58
Average cost per lineal foot for completed stream bank protection work	1.17

*Compiled by Jules Renaud, Southern Utah Area Forester 3/9/40

Pictures - Utah 543 and 543A

The following comments* pertain to the bank protection work on the Price River illustrated in these pictures. This job was done by Camp SCS-3-U labor and was completed in March 1939. Douglas fir piling from the Price watershed was used. The trees used in connection with the piling are native cottonwood from the grove seen in the background of the pictures.

There is 700 linear feet of bank protection work, the total cost of which was $1,054.57, or approximately $1.51 per foot. This cost included $117.00 worth of cable, cable clamps, diesel fuel oil, gasoline, and 63 native Douglas fir piles which were cut by the CCC camp and later charged out of storage at $2.50. The above cost does not include tree planting.

The low water channel continued in its original position under the cut bank until a flood in September 1939. At that time a load of silt estimated at 30,000 cubic yards, was deposited behind the revetment forcing the low water channel to stay away from the farm lands and establishing a new channel bank. In this deposited silt 2484 trees were planted including native tree willow cuttings, Russian olive, wild plum, and sandbar willow. These trees can be distinguished in the repeat picture although they are partially hidden by weed growth.

Landowners require some help in this type of treatment as heavy equipment, such as a caterpillar tractor, dragline and pile driver, is used. Piling is satisfactory where soil conditions allow driving. Wooden piling is not usually satisfactory in a stream bed consisting of large boulders.

On the Price River where an acute bend was made and a channel cut was not feasible this type of treatment has proved its ability to hold when a sufficient number of large trees have been used to face the structures. The trees shown in these pictures are only average in size, and if larger trees can be secured, they should be used without having the branches cut off.

*Compiled by Blaine C. Morse, District Conservationist, Price, Utah

STREAM BANK PROTECTION STRUCTURES USED ON THE SALT LAKE AREA*

The plan of treatment for both large and small streams in northern Utah included:

1. Clearing all obstructions from the main channel.

2. Constructing flexible revetments by use of native willow brush and cottonwood trees.

3. Sloping the stream banks where it is possible.

4. Planting behind revetments and along unprotected stream banks.

5. Fencing the stream from grazing livestock.

Two slightly different types of revetment have been used for large streams. Their use depended on the nature of the stream bank cutting at the particular location to be protected. In both types, live-willow brush from 2 to 3 feet in thickness were placed as a foundation along the present or intended stream bank. This mat had a minimum of 1 foot compressed thickness. Cottonwood logs 16 inches in diameter and from 12 to 16 feet long were placed on the willow brush mat and anchored by cable to a deadman or section of cottonwood log buried on the stream bank. The logs in the revetment overlapped each other up to, but not exceeding, half their length. See photographs of bank protection on Gordon Y. Craft and L. T. Gustaveson farms.

Type A (See following sketch)

The revetment was located out from the stream cut bank to allow for the development of a smooth curve in the channel. The cottonwood logs for this type were attached to a 7/8- or 1-inch master cable by a single strand of a 6-strand cable. Lateral or bracing cables were attached to the master cable and anchored to deadmen back on the bank.

In addition, large cottonwood logs were clamped to the bracing cables to cause silting in back of the main revetment during high water. This silted area was planted to willow and other suitable species.

Type B

This type is suitable for the protection of stream banks that are cutting on straight stretches of the channel or on normal stream curves. The mat of willows is placed at the base of the stream bank with the butts of the willow stems in close contact with the bank and the tops pointing

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*Compiled by George D. Swainston, Area Forester
R. O. Dobbs, Assistant Agricultural Engineer

slightly downstream. If possible, vertical banks should be sloped to allow a soil cover for the butts of the willows in the revetment and for a location on which to plant tree willow cuttings or rooted stock. Stream bank plantings to be most effective should be planted near the base of the bank and sufficiently close to water to insure establishment. Cottonwood logs are placed on the willow mat and anchored by a single strand of cable to a deadman on the bank. Two ties are made for each log, one at the butt end of the log and another about 1/3 distance back from the butt end.

The total cost, as reported for 3740 feet of cable, log and brush mat revetment on the L. T. Gustaveson farm on the Weber River, is $2,024.04. Of this amount $114.97 is listed for materials. Unit cost is $0.54 per linear foot. This cost is exclusive of any planting or stream fencing.

For small streams several methods, or rather "variations", of anchoring willow mat revetments or individual log revetments can be used effectively. On straight courses of eroding channel and where the force of the stream is not too great on the revetment, live-willow brush can be placed on an angle at the base of the stream bank and anchored sufficiently by earth pushed over the butt ends. The live-willow mat silts up, takes root and soon becomes firmly anchored. It forms a dense protective buffer against stream cutting action.

On badly eroded curves, the willow mats can be placed and anchored as illustrated by the attached drawings.

On small streams at locations where stream bank cutting is not too active, one or two cottonwood logs tied in close to the stream bank will be sufficient protection until plantings are established. Such locations might be fairly low banks, partly sodded or vegetated, and not receiving the full force of the current.

Pictures - Arizona 3515 and 3515B

Tetrahedrons have been used extensively on the Gila and San Carlos Rivers. Where they are used in front of cut banks to establish a new bank, some means of slowing down the water behind the structure is necessary to prevent scour. In the work shown in picture 3515 logs supplemented by planting were effective in controlling the old channel area. In the fourth San Carlos illustration (opposite Ariz. 3053) it will be noted that some of the tetrahedrons extend higher than those on either side. The high ones were anchored on one corner to a driven rail piling. Those not anchored have settled. Planting within the triangle formed by the tetrahedron also helps in preventing settling. The cost of tetrahedron lines on the Eastern Arizona Area, based on actual operations, is $3.78 per linear foot. Average costs of various types of treatment are listed below:

	Cost per Linear Foot*
Rail and cable tetrahedrons	$3.78
Driven rail, cable and wire fence	2.00
Log and cable revetment (logs on site)	1.75
Rail and wire, rock-filled jetties	6.75
Planting willow post cuttings	.35

Spacing at $1\frac{1}{4}$ foot intervals may be used in addition to and in combination with above types.

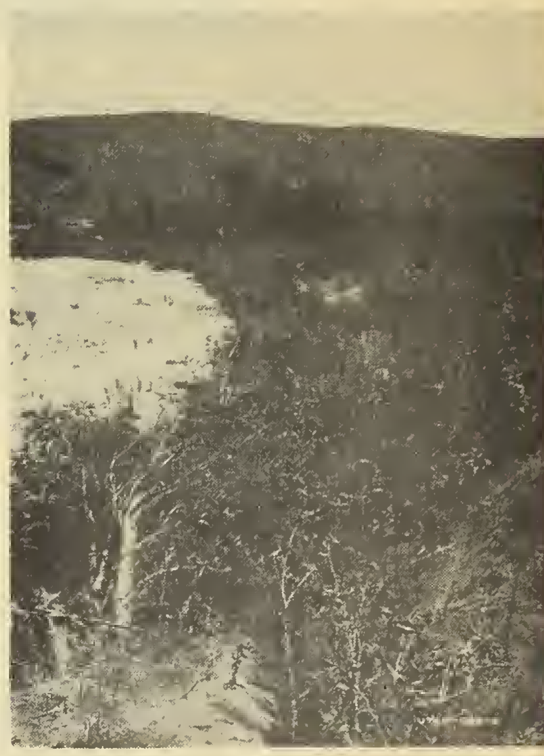
*Compiled by William G. Stambaugh

Gordon Y. Croft farm on Weber River, Utah. A live willow brush mat held in place by anchored logs has been placed on a curve to hold the bank from cutting. This work was done and picture taken during the winter of 1941. Black willow cuttings were planted behind revetments. Russian olive was planted on several areas behind the front line of willows. The river bottom was fenced to keep out livestock.

Utah 684 - 12-14-39

Leland Bringhurst farm. Juniper tree and cable bank protection 6 months after work was finished. First flood deposited silt to a depth of 1 to 4 feet behind cabled Juniper trees. La Verkin Creek, Toquerville, Washington County, Utah.

L. T. Gustaveson farm. Live willow brush mat held in place on bank by anchored log. Installed winter and spring of 1940. Brush mat caught considerable silt and started growth forming a living barrier against stream. Construction was similar to that shown in preceding picture taken on the Gordon Y. Croft farm. Picture taken summer of 1941.



Utah 684B

Same location as shown in 684. Taken about September 1, 1940.

Utah 380A - 7-18-38

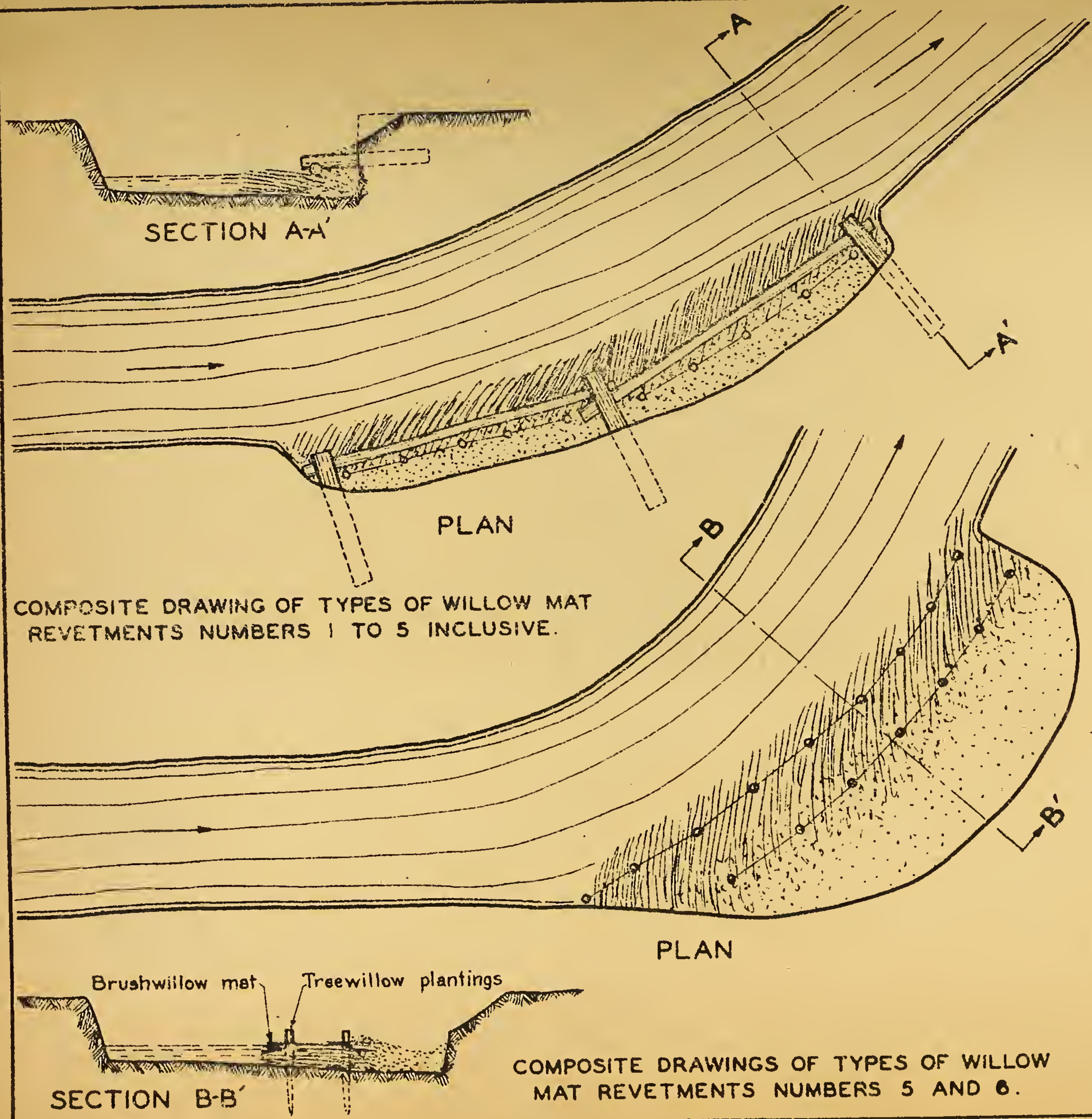
Brush mat and willow planting. Vertical cuttings planted spring of 1938. East Canyon Creek.

Utah 380C - 8-40

Repeat of 380A in third growing season. A stable stream edge has been established.

Native vegetation west of San Jose Diversion, Gila River, Arizona. Looking upstream. A natural, controlled channel illustrating desirable open channel width with vegetation on both sides. Right side of stream most subject to cutting and adjacent to irrigated fields. Left side unprotected from grazing and in poor condition. Proper care and maintenance would involve protection from grazing, planting to widen vegetated strip, and fill in gaps. Over-mature trees should be replaced with young growth. Stream is self-cleaning and will overflow banks without eroding them.

Dudley willow (Salix gooddingii) on Gila River, Wilson farm, east of Duncan, Arizona, bridge. Cultivated fields lie behind this willow belt. This strip of willow is about 30 feet wide and 1/2 mile long. The willows are about 40 years old and were planted by Mr. Wilson along outside edge of curved bank. Mr. Wilson, in addition to planting, has applied systematic maintenance to keep this barrier in perfect condition for protecting his farm. The willows are protected from stock. A similar protection on opposite side would give river a uniform channel width and prevent unregulated meandering.



COMPOSITE DRAWING OF TYPES OF WILLOW MAT REVETMENTS NUMBERS 1 TO 5 INCLUSIVE.

COMPOSITE DRAWINGS OF TYPES OF WILLOW MAT REVETMENTS NUMBERS 5 AND 6.

TYPES OF WILLOW MAT REVETMENTS

1. Angled brush willow mat secured in place by earth on butts and longitudinal cottonwood pole which is in turn held down by notched transverse pole trenched into bank.
2. Same as No.1 except that tree willow longitudinal poles are used.
3. Same as No.1 with addition of one row of post tree willow plantings.
4. Same as No.2. with addition of one row of post size tree willow plantings.
5. Angled brush willow mat secured in place by earth on butts and held down by wire tied to one row of post size willow cuttings.
6. Angled brush willow mat secured in place by earth on butts and held down by wire tied to two rows of tree willow post size plantings.

Note:

In addition to being used close to cut banks, types 5 and 6 may be used away from banks.

To facilitate construction during high water, willows may be wired into bundles before being placed into streambed.

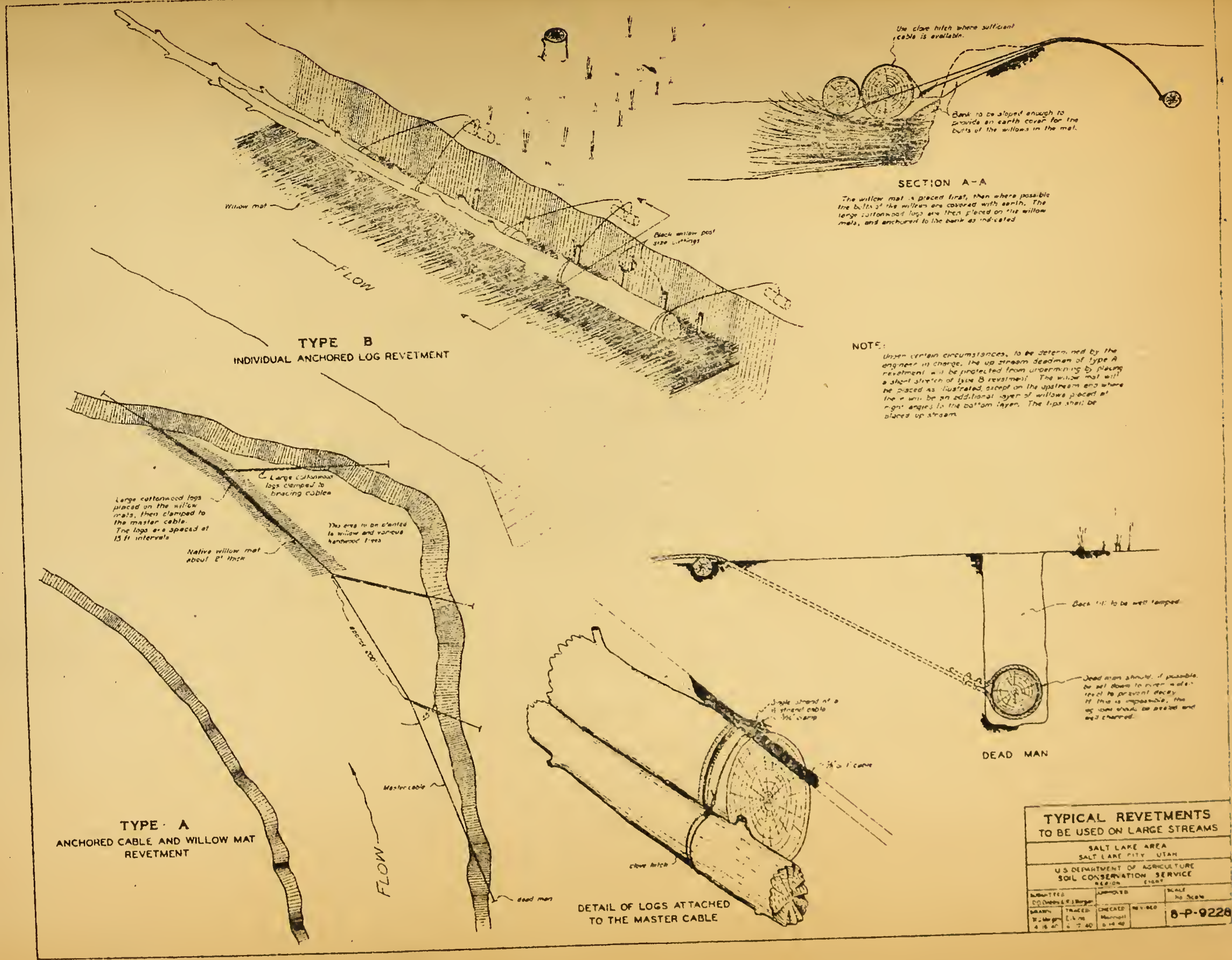
WILLOW MAT REVETMENTS
WEBER RIVER DEMONSTRATION AREA

UTAH PROJECT
SALT LAKE CITY. UTAH

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
REGION EIGHT

APPROVED:			SCALE: 1" = 10' APPROX.	
DESIGNED: R.O. Dobbs Swainston	TRACED: Elkins 2-9-39	CHECKED:	REVISED:	L-994

L-8199


Use clove hitch where sufficient cable is available.
Bank to be sloped enough to provide an earth cover for the butts of the willows in the mat.
SECTION A-A
The willow mat is placed first, then where possible the butts of the willows are covered with earth. The large cottonwood logs are then placed on the willow mats, and anchored to the bank as indicated
Willow mat
Black willow post size cuttings
FLOW
TYPE B
INDIVIDUAL ANCHORED LOG REVETMENT
NOTE:
Under certain circumstances, to be determined by the engineer in charge, the up stream deadman of type A revetment will be protected from undermining by placing a short stretch of type B revetment. The willow mat will be placed as illustrated, except on the upstream end where there will be an additional layer of willows placed at right angles to the bottom layer. The tips shall be placed up stream.
Large cottonwood logs clamped to bracing cables
Large cottonwood logs placed on the willow mats, then clamped to the master cable. The logs are spaced at 15 ft intervals
This area to be planted to willow and various hardwood trees
Native willow mat about 2' thick
Back fill to be well tamped
Dead man should, if possible, be set down to river water level to prevent decay. If this is impossible, the log used should be peeled and well charred.
DEAD MAN
Master cable
dead man
TYPE A
ANCHORED CABLE AND WILLOW MAT REVETMENT
FLOW
clove hitch
DETAIL OF LOGS ATTACHED TO THE MASTER CABLE
TYPICAL REVETMENTS
TO BE USED ON LARGE STREAMS
SALT LAKE AREA
SALT LAKE CITY UTAH
U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
SCALE
No Scale
8-P-9228

Utah 683 - 12-14-39

Black willow cuttings planted behind cabled tree protection. E. R. Frei farm near Santa Clara, Utah.

Utah 683-B - 5-27-40

Cabled tree willow planting bank protection. Deposit of 4 feet of silt behind cabled trees from one moderate flood in period of 6 months. Area behind protection planted to willow cuttings, rooted trees and shrubs. E. R. Frei, Sr. farm, Santa Clara, Utah.

Utah 683-C - 10-2-40

Repeat picture of location shown in picture above. Near end of first season.

Utah 601 - 3-14-39

Individual cottonwood trees anchored back into solid bank, each tree to an individual deadman. Willow planted in silt bar formed. Virgin River, Antone Neilson farm.

Utah 621 - 9-13-39

Same site as Utah 601 and 601B showing front view of silt deposit in limbs and willow growth near end of first growing season. Willow planting should be extended to form wider belt.

Utah 601B - 10-12-39

Same site as Utah 601. Bank sloped to build dike on field border. Willow now 6 feet high were planted April 1939 in 18 inches of silt deposit which collected in tree branches.

Utah 621B - 8-40

Same location as Utah 621. Second growing season.

Utah 602 - 3-14-39

Cottonwood tree anchored under cut bank on Antone Neilson farm, Virgin River, Southern Utah Area. Cable fastened to deadman 40 feet back from bank.

Utah 602B - 10-13-39

Willow planted in April 1939 in silt that collected soon after large cottonwood trees were cabled to cut banks. Same location as Utah 602.

Utah 602C - 9-40

Shows continued growth of vegetation on established bank.

Utah 543 - 8-3-39

Piling, cable and tree revetment on Price River. The stream formerly followed along bank to the right of present position. To protect farm land, wooden piling was driven along proposed stream edge and faced with trees. Two cross jetties were put in to assist in stilling and desilting water to build up old channel location. A short pilot channel was opened to change channel alignment to a flatter curve. When picture was taken, the low water channel passed through this pervious revetment and followed under the cut bank bordering the field edge. A gravel dyke or impervious structure placed at the head of cut-off would have accelerated the new channel formation.

Utah 543A

Repeat of Utah 543. Taken during summer of 1940. In September 1939 a flood flow deposited an estimated 30,000 cubic yards of silt behind the revetment, forcing the channel to the new designed alignment in front of piling and tree and cable revetment. In the spring of 1940 2,484 trees and cuttings were planted to form a long-life barrier which is expected to hold the channel in its new position.

Arizona 3515 - 2-38

San Carlos River, looking down ~~upstream~~. Bank protection designed to protect Indian farm lands and to aid in deposition on flood plain during flood. Side wash comes in at right corner of picture; San Carlos River from left. Stub jetty on left designed to take pressure off main structure where river strikes on curve. Former stream edge visible behind wire-faced tetrahedron line. Logs across old channel placed to cause deposit. Horizontal and vertical cuttings planted along these barriers are visible in picture; also rows of willow planted parallel to structure.

San Carlos River

This picture, a repeat of 3515, taken in early spring of 1941 shows the area between the stub jetty (just off left edge of picture) silted full and the planting on the established channel edge vigorously growing. Two flood flows in the spring of 1941 deposited from 2 to 6 feet of silt in the flood plain area behind the protected stream edge. The larger flow was estimated at about 35,000 second feet.

San Carlos River - 1-15-41

This picture taken at a different angle from river side to show deposit on the stub line shown in picture 3515. Debris has lodged on the stub jetty and silt has been deposited between the stub jetty and the main tetrahedron line level with the top of the structure. Most of this deposit occurred during the first or smaller flood in January 1941. The line of willow behind the main structure can be seen extending from the right center of picture to the left center.

San Carlos River - 9-41

Structure and planting made in 1938. Front of planting washed out due to current action behind structure during flood. Should be replaced as maintenance measure.

Arizona 3053 - 8-37

Marshall Farm, Pima, Arizona. The Gila River was cutting into irrigated farm land. A vertical bank had developed. Mr. Marshall strung two strands of cable on pipe driven into the river bed under the vertical bank. To this cable were wired branches of native trees with tops angled upstream to encourage silt deposition. This type of protection worked very well on the gentle curve where it was used. The willow cuttings were planted in March 1937.

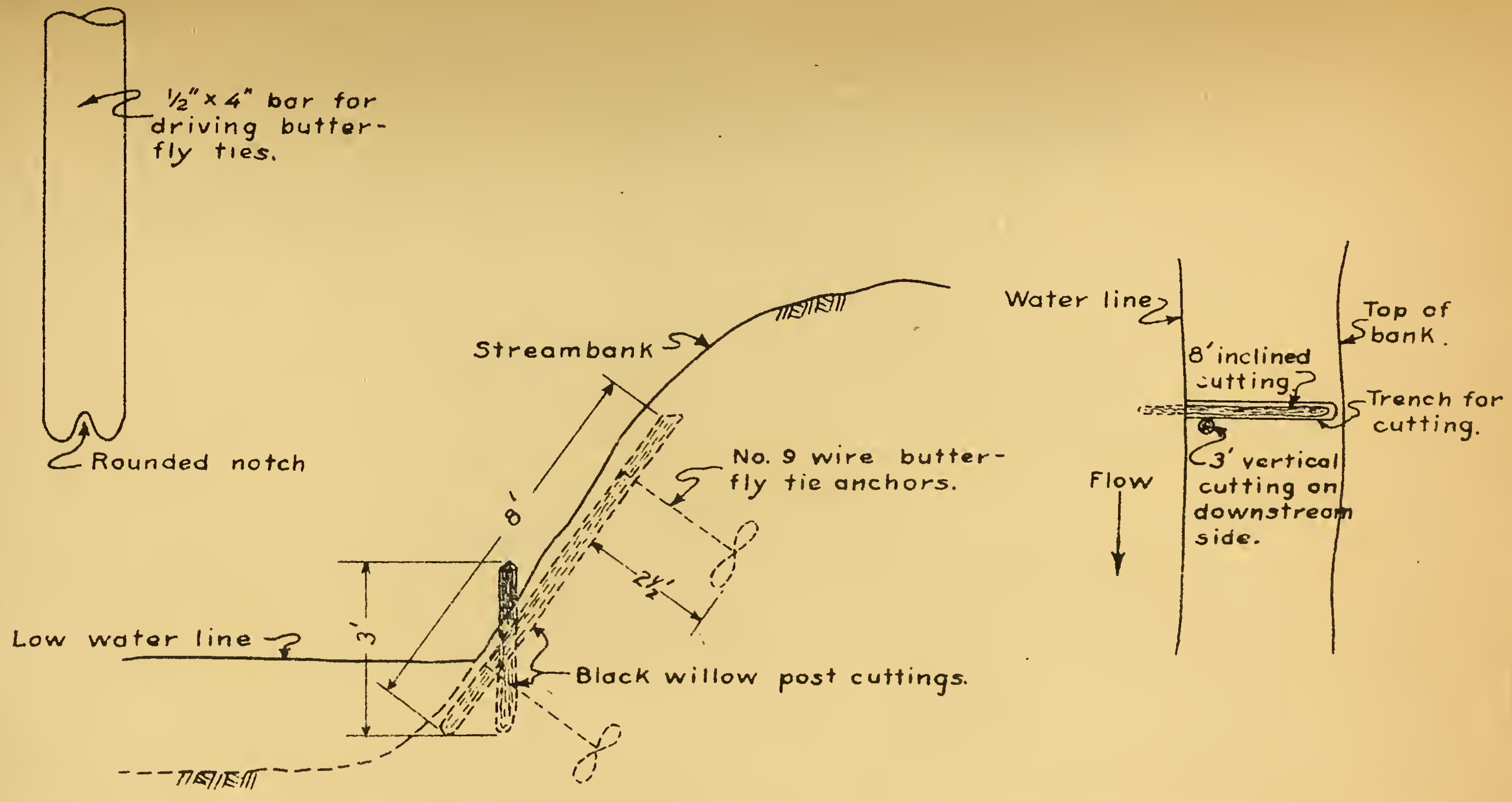
San Carlos River - 9-41

Three year old plants partially washed out by flood. Note exposed roots. Space between rows should be broken up by staggered planting to prevent development of swift current between rows.

Arizona 3054 - 8-5-37

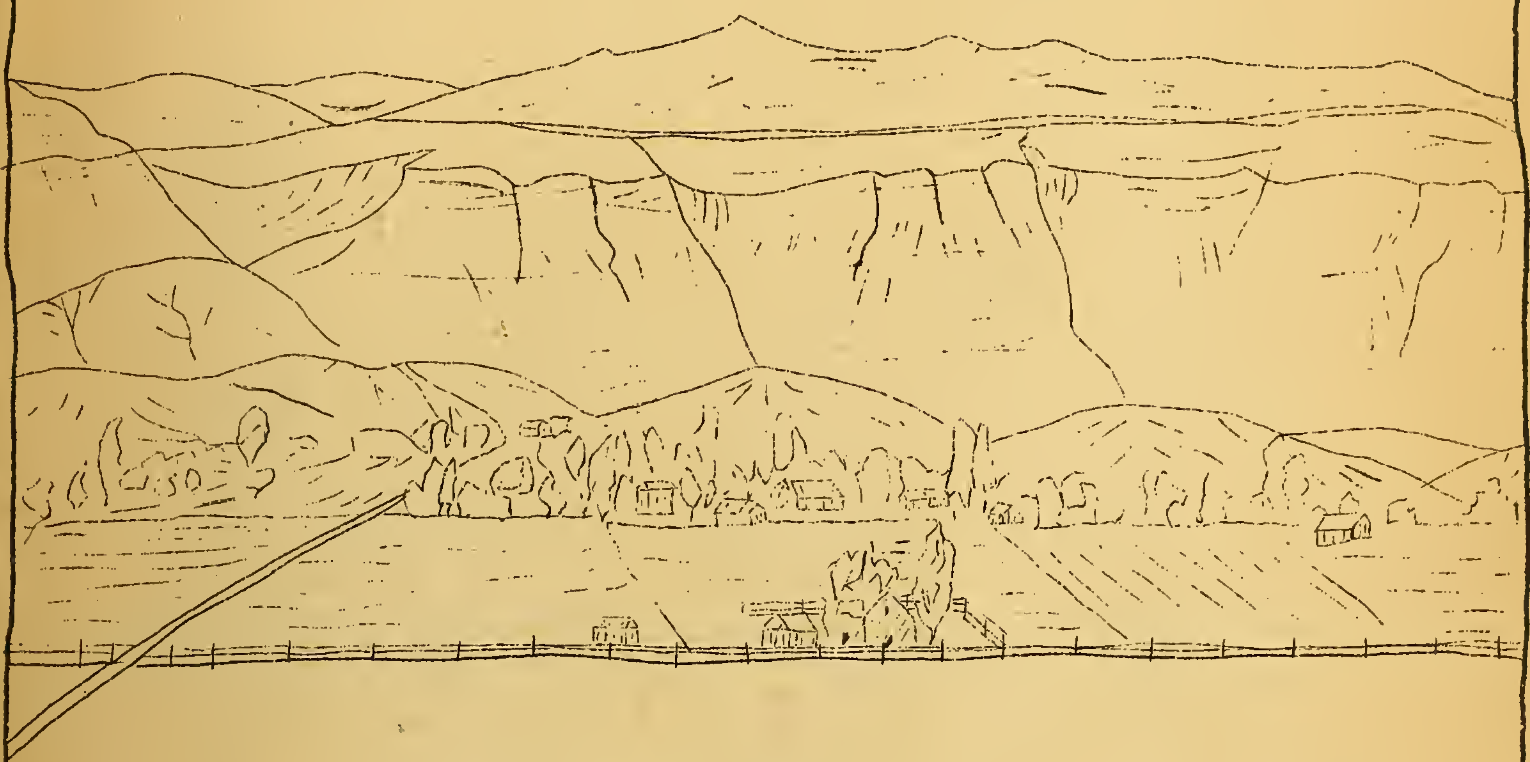
Marshall Farm, Pima, Arizona. This is a more distant view of the Marshall bank protection shown in picture 3053. Taken during low-water period.

WORK ORDER NO. ______



NOTE:
Post cuttings to be Black Willow.
3' vertical cuttings to planted 2½' deep on lower side of inclined cuttings. 8' inclined cuttings to be planted in shallow trench and anchored to bank by use of No. 9 wire butterfly tie anchors driven into bank 2'6" deep. Attach ties to cutting at 2' from either end.

PLANTING TECHNIQUE FOR SLOPED BANKS				
U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE REGION EIGHT				
EASTERN ARIZONA AREA SAFFORD-ARIZONA				
REFERENCE:			SCALE: NOT TO SCALE	
DETAILED W.G.S. 2-25-41	TRACED E.G.D. 2-28-41	CHECKED J.N.T. 2-28-41		FILE NO. 8-L-2800



ENGINEERING PRACTICES

Flood Protection in Narrow Valleys

K.F.K.

Contributed by
U.S.Department of Agriculture
Soil Conservation Service
Region Eight
Southern New Mexico Area
Las Cruces, New Mexico

Flood Protection in Narrow Valleys

The floods of September 1941 in the Southern New Mexico Area have shown surprising effects of terraces and cross dikes in their protection of land subjected to flooding to depths of two feet to four feet. In the numerous cases of terraced fields observed, no gullying occurred; erosion was limited to occasional washing in the lower sides of the terrace slopes; the stream returned to its former channel; and the silting in the terraces consisted of fine loam and soil. These conditions were in decided contrast to the formation of gullies, and even new stream channels, and the deposits of gravel and rocks over large areas of the flooded fields that were not terraced. These results are the basis of the following plan of flood protection for narrow valleys, which will furnish adequate protection at reasonable costs, and which can be done by the landowners with equipment usually available and without undue proportion of material cost.

The system is planned primarily to protect the cultivated lands, both irrigated and non-irrigated, in relatively narrow valleys, adjacent to permanent or intermittent stream channels in which the frequent flash run-offs are often of flood proportions. The areas in the valley floors suitable for cultivation are narrow, and the construction of a channel, with the necessary dikes, sufficient to carry the flows of even 3 - 5 year frequency, would require an excessive portion of the valley width without furnishing protection against the greater flows.

The system consists of three essential parts -

1. Channel improvement or construction to capacity sufficient to handle the peak run-offs of the average year. These channels should not have side dikes parallel, or adjacent, to the channel. The channel itself to be kept clear of all vegetation except grass and sod.

2. Relatively large dikes across the valley floor, sufficiently high not to be overtopped by the 3 - 5 year frequency floods. These dikes should be planted to permanent vegetation, and can probably be located on the property lines.

3. All fields to be terraced or bordered with intermediate cross dikes or low terrace borders, located as closely as possible at right angles to the stream channel. Any terrace or other borders approximately parallel to stream channel to be lower than borders at right angles to the channel.

The attached sketch map shows a layout of the system for a valley in which the stream channel meanders from one side to the other - a general condition - and in which irrigation ditches are diverted at the points where the channel is at, or close to, the side of the valley, as is frequently the case. Typical sections are also shown.

1. CHANNEL. The stream channel section should be sufficient to carry the peak run-off of the average year with the maximum water level at, or slightly below, the adjacent land level. Where channel grades absolutely prevent this condition, the channel dike, or dikes, should not

be carried more than 0.5 feet above the probable water surface, and will serve as soil saving dikes to raise the field level; any such channel dikes should never be more than 2.0 feet maximum above the field level. While such dikes afford some protection, these are frequently the cause of greater damage in preventing the return of flood water to the normal channel, creation of new channels and gullies, and damage to crops from ponded water. The stream channel itself must be kept clear from all vegetation - trees, shrubs or high weeds that obstruct the flow. Lines of trees and heavy shrubs, along the banks, parallel to the channel will catch debris and act as dikes preventing the return of flood water to the channel section, and are frequently the cause of the formation of new channels. Low shrubs and heavy grasses, it is believed, are preferable for protection of the channel banks of the Penasco River which has been the basis of this study.

It is probable that channel grade stabilization structures (in addition to the control of any irrigation ditch diversions) may be needed. The need for, and location of such structures will be governed by particular conditions, but it is recommended that such structures be located in line with the larger cross dikes, or that such a dike be built opposite the grade control structure.

2. DIKES. The location of the larger cross dikes across the valley floor will depend upon the grade and depth of the stream channel, the slope of the land, and the width of the valley floor. A maximum spacing of 1,000 feet for the average valley slopes and less for the steeper slopes is suggested; a dike should be placed at each point where there is a definite and considerable increase of land slope. When there are dikes, on both sides of the stream channel, the channel ends should be directly opposite each other, and the dikes located in the same general line. The height of these dikes at the stream channel is dependent on the channel grade, the spacing between dikes, and the slope of the land above, both parallel to the line of channel and across the valley floor. The top of the dike must be level. Maximum heights of 4 feet to 6 feet are suggested. Minimum top width of 4 feet; upstream slope of 2:1 and downstream slope of 3:1 is suggested. The flatter downstream slope is used for protection in the occasional cases of overpour; the dikes should be planted to permanent vegetation and lines of trees below and/or above if desired. Trees and fences should not be placed on the tops of the dikes. The ends of these dikes may require riprapping. The tops of all dikes must be level, and the dikes must be continuous from channel end to hillside, and without openings. In irrigated areas, it will be necessary for ditches to pass through some of the dikes. This should be done in culverts or boxes, of such size that their full capacity is the normal amount of irrigation water. Backfill of such structures should be thoroughly and carefully tamped to prevent breaks in the dikes during floods, and concentrations of flow down the valley through the ditch channels.

3. TERRACES AND BORDERS. Intermediate terrace borders or smaller cross dikes across the valley floor should be placed at intervals of not over 300 feet (preferably less) depending on land slopes and field arrangement. When borders more or less parallel to the stream channel must be used for land management, these should be lower than the borders or cross dikes at right angles to the stream channel. These terraces or borders may have sections similar to broad base terraces so that their surfaces can be included in cultivation, or may be ridges for irrigation borders. Maximum heights of 3 feet for intermediate cross dikes and 18 inches for terrace borders parallel to the stream channel are suggested. The tops of all these borders or small cross dikes must be level.

When cross dikes, or intermediate borders are used as soil saving dikes, and it is necessary to drain surplus ponded water, the drains should be closed boxes or conduits, not open cuts or ditches, and should be relatively small (not over 12 inches square in the major cross dikes) and backfill must be thoroughly tamped.

4. IRRIGATION DITCHES. Ditch headings should be located at end of one of the larger cross dikes when possible; these dikes will be on locations required by land slopes, field arrangement and topographical conditions; if the ditch diversion cannot be so located, or if the location of the nearest dike cannot be changed, an extra cross dike should be built. Because of the stream channel grade control from the sill of the diversion structure, those dikes at or opposite ditch headings may need to be 1 foot or 2 feet higher than the other cross dikes in the system. Ditch outlets should be made through closed boxes or conduits, limited to the size needed for the normal irrigation flow to prevent flood flows scouring the ditch channel.

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The performance of the complete system can be predicated for the three general types of flood conditions.

A. The average seasonal run-offs will be carried by the stream channel, with the cross dikes at the ditch headings confining the flow to the channel and preventing the higher water level above the controlled grade at the diversion heading sill from flowing across the fields; and with the controlled ditch outlets preventing excess flows in the ditches.

B. The occasional (3 - 5 year frequency) run-offs will exceed the normal channel, and flood parts of fields and areas between the large cross dikes, but will be confined between these dikes and the flow down the valley limited to the channel opening at the ends of the dikes; velocity of flow down the valley on the fields will be reduced and scouring of fields between the larger cross dikes will be prevented by the small cross dikes and terrace borders. As the depth of flood decreases, the flooded areas will drain laterally to the channel, probably without any extended periods of inundation of crops due to the "flash" characteristics of these floods. Silt deposits on fields will be fine silt and loam, with the heavier damaging gravel and rocks confined to the channel.

C. Excessive floods may overtop all the cross dikes and all areas between them, but the level tops will prevent concentrations of flows and the dikes will reduce velocity so that there will be little, if any, erosion or soil loss of the protected areas. Increased velocities of current due to greater depth of water and free flow conditions in the channel will probably cause scouring and enlarge or maintain the channel section.

The condition of terraced fields in the recent floods has shown that ordinary earth field terraces with heights of 18 inches to 4 feet above the land level on the lower side, can withstand flood overpours of 2 to 4 feet and subsequent small drainage flows of 2 to 3 weeks duration, without damage other than incidental cutting on the downstream side of the terrace.

For all run-offs flooding the cultivated lands, the cross dikes and intermediate dikes will act as soil saving dikes, causing fine silt and loam deposits in the areas between them; due to reduced flow velocities, except in the channel, deposits of damaging gravels and rocks will be in, or close to, the normal channel. The deposit of silt and soil will raise the general land level (more rapidly in the areas more frequently flooded) and, as the land level rises, the cross dikes, intermediate terraces and borders should also be raised to the necessary heights above the new land level. The intermediate terraces and borders can, and will probably, be raised by, and during, farming operations; the larger cross dikes should be raised before the next flood season.

There will undoubtedly be another valuable result of this treatment in the reduction of the flood peak in all flows which exceed the normal channel, due to the detention effect of the cross dikes. In a valley of which approximately three quarters of a mile has been treated with cross terraces the flood peaks and flows from a side arroyo have been dissipated and reduced to amounts which have not caused any damage below the treated area. The value of such reduction of peak flows will probably be greatest in the intermediate flood flows, in the reduction of crop damages.

The results after a period of years will be a gradual raising and levelling of the cultivated lands, with an adequate normal stream channel below the adjoining land level, eliminating any need for channel dikes and permitting free and quick drainage of flood water.

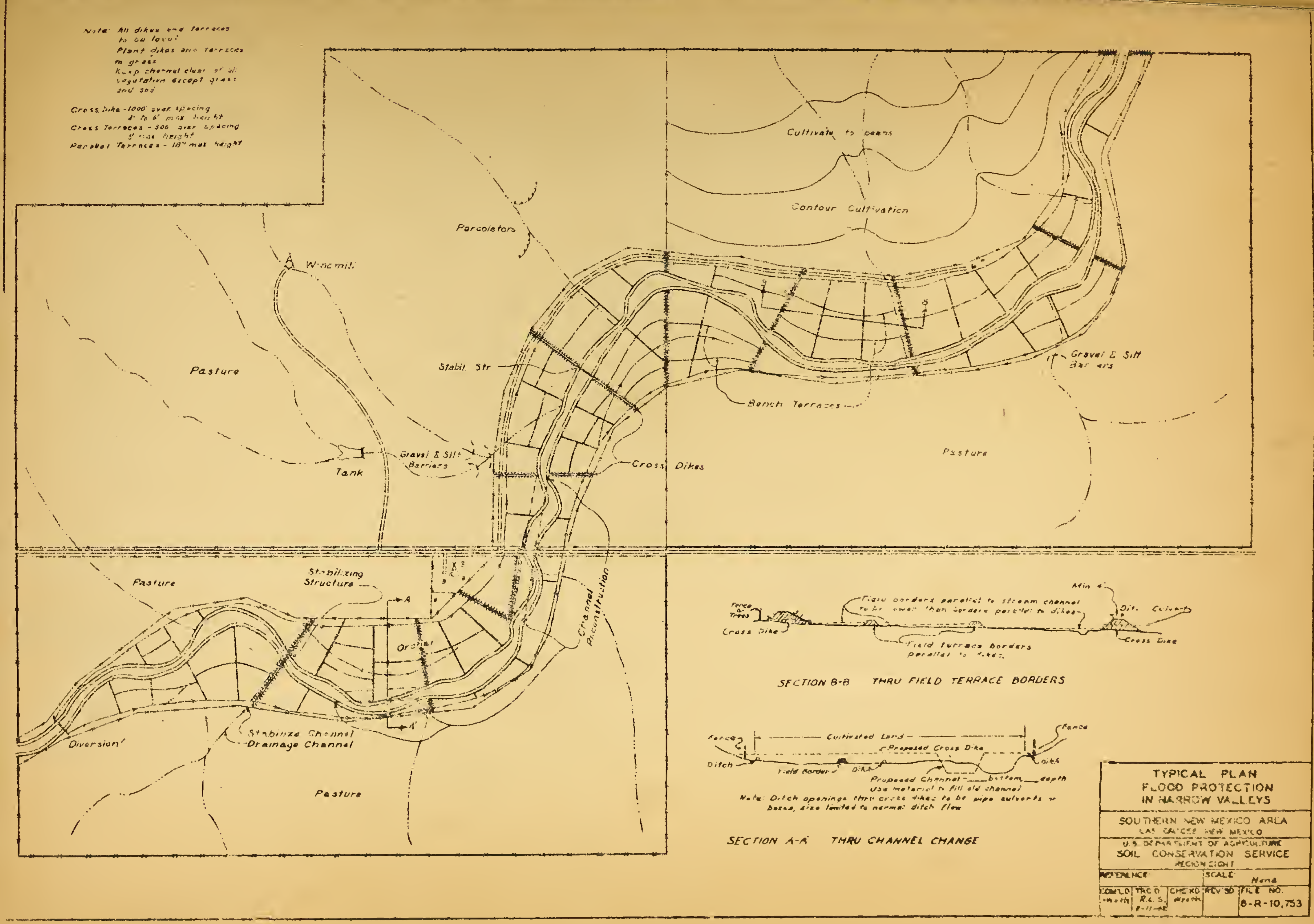
The system will require maintenance, but the greater part will be in connection with regular cultivation methods, as maintaining the intermediate dikes and terrace borders.

It is believed that the system outlined will, at reasonable cost, provide adequate protection under all conditions, will prevent erosion of the soil, and will improve soil conditions in the fields from silt deposition.

The program outlined to provide flood protection is intended to operate in conjunction with, and is dependent upon, other soil conservation practices on both the lands protected and the tributary watersheds. The control and protection of watershed areas by proper management and structural treatment where required is necessary to reduce the run-off peaks and the amounts of flood debris; in particular, side drainages should be treated with silt barriers, and detentions to reduce the volume of rocks and gravel carried to the main valley. On the lands protected from flood damage, conservation practices for protection against soil losses are equally important. In such operations, other types of treatments and structures can be used to advantage in conjunction with the structures outlined.

While solid protection dikes, along and parallel to, the stream channel are undesirable because they prevent the return of flood waters, permeable dikes (rock or brush) can be used to advantage to raise the adjacent land level. Where the land is relatively low (and where an adequate channel of sufficient capacity below the land level cannot be established

because of grade or other conditions), a brush percolator or similar structure will be more effective than earth dikes. It will permit the more frequent floodings usual on such low areas to drain off but will retain the silt; the more frequent floodings and resulting silt depositions will raise the land level, and produce the necessary stream channel. If earth soil saving dikes are used, the tops should be level along the entire length and any drains should be boxes, not open drains.


Note: All dikes and terraces to be level
Plant dikes and terraces in grass
Keep channel clear of all vegetation except grass and sod
Cross Dike - 1000' aver. spacing 4' to 6' max height
Cross Terraces - 300 aver. spacing 5' max height
Parallel Terraces - 18" max height
Cultivate to beans
Contour Cultivation
Parcolators
Windmill
Pasture
Stabil. Str
Gravel & Silt Barriers
Tank
Cross Dikes
Bench Terraces
Pasture
Stabilizing Structure
Orchard
Channel Reconstruction
Stabilize Channel Drainage Channel
Diversion
Pasture
Pasture
SECTION B-B THRU FIELD TERRACE BORDERS
Field borders parallel to stream channel to be lower than borders parallel to dikes
Field terrace borders parallel to dikes
Cross Dike
Cross Dike
Culvert
SECTION A-A' THRU CHANNEL CHANGE
Fence
Ditch
Cultivated Land
Proposed Cross Dike
Field Border
Dike
Proposed Channel - bottom depth
Use material to fill old channel
Note: Ditch openings thru cross dikes to be pipe culverts or boxes, size limited to normal ditch flow
TYPICAL PLAN
FLOOD PROTECTION
IN NARROW VALLEYS
SOUTHERN NEW MEXICO AREA
LAS CRUCES NEW MEXICO
U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
REGION EIGHT
REFERENCE
SCALE
None
TRC'D
R.L.S.
CHK'D
REV'SD
FILE NO.
8-R-10,753

#2257

EROSION OF STREAM BANKS

By

Lloyd B. Smith
Civil Engineer

Topeka, Kansas

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Reprinted from Proceedings of the Kansas
Engineering Society, 1929

EROSION OF STREAM BANKS

by

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Synoposis

This paper deals with the phenomena in relation to the erosion of the banks of streams running through alluvial or sandy soil. The various currents in a stream are discussed and the effect of these currents in detaching the solids from the bank, and in transporting, distributing and depositing these solids. It is determined that a sloping or stepped bank is necessary to a satisfactory system of bank protection. The principles and general conditions to be met in the design and location of permeable dikes are set forth.

Introduction

The importance of the transportation of alluvium, silt, sand and other solids by surface waters is out of proportion to the effort that is being made to remedy this undesirable action. There are but two sources for the renewing of the supplies of solids in our water courses. One is the alluvium carried from the surface soils in every freshet, and which is a matter of supreme importance to the oncoming generations; the other is the erosion of the stream banks. If the soil from the surface wash can be kept on the land and the banks of the streams can be kept from eroding, thus destroying the source of new material delivered to the water courses, their regimen will be established, their channels will become cleared of bars and deepened, their capacities will become increased and the periodical losses from floods will be lessened. Because of the increased value of land and especially of the improvements on the land adjacent to rivers and smaller streams, the stabilization of caving banks has already become of prime importance, and to this division of the problem this paper is directed.

River Currents

As the automobile furnishes the power and is the transporting vehicle while the passenger directs the course it takes, so in streams the water furnishes the power and is the transporting vehicle while the solid material, as the passenger, is an important factor in determining the course of the stream. The location of the route the water takes will first be considered; then the method by which the transported solids direct it into this path.

In alluvial valleys all streams have similar and characteristic courses (Fig. 1). At a high water stage, short of overflowing its banks, the current strikes one bank (a), is deflected and crosses over to the opposite

bank (b), only to be deflected again. The repetition of this process, varying only in degree, continues for the length of the valley. Assume a longitudinal filament of water of unit cross section at the surface of the swiftest part of the stream (a, Fig. 2). When it strikes the bank on the outside of the curve of the stream, its energy is exerted in two directions, one a pressure (b, Fig. 2) normal to the bank, the other (c) a deflection of the current parallel to the bank. The resultant current (c) is (a) changed in direction and reduced in velocity, while (b) resisted by the bank, causes an elevation of the surface of the stream adjacent to the bank. This resolution of forces applies to the stream as a whole and results in a cross section at the bend of the stream as shown in Fig. 3.

The water at (a) in this superimposed head seeks its own level. The solid material of the bank prevents its movement on the shore side; the gradient of the stream prevents on the up-stream side; it can escape down-stream with the advantage of the stream gradient, but its shortest course and steepest gradient is toward the lower water surface of the cross section at (b) and toward this point it seeks equilibrium. The oncoming current (c) holds this tendency toward adjustment hard against the bank and forms the downward current (d), which, affected by the general movement of the water down-stream, takes a diagonal course down the face of the bank.

This action of the water flowing in a curved channel was noted by Prof. James Thompson in 1877. (Encyclopaedia Britannica, 11th Edition, Vol. XIV, P. 72). A curved trough was built (Fig. 4) and a stream of water maintained through it. Seeds, with about the specific gravity of water and saturated in a soluble dye, were placed on the bed of the stream and their paths noted. It was discovered that seeds placed at various points (c, Fig. 4) took diagonal courses across the bed of the stream and were deposited on the inside of the curve of the stream.

Stream Solids

In considering the solid material which is the passenger in the stream, varying in size from boulders to dust, it is well to consider first why these solids, heavier than water, are carried at all. There are two distinct methods of transporting the solids. There are the solids that are in close proximity to the bottom, commonly called "bottom load." The force of the current on the up-stream side of each particle rolls or slides it along the bottom; again, there are the particles that are distributed through the water even to the surface. In Fig. 6 is illustrated a longitudinal section of a stream. Corrugations in the sand caused by friction are familiar to all in places where a sand surface has been exposed to either air or water currents. The heavier solids roll over the corrugations and come to repose at the foot of the elevation as at (a). Lighter grains describe the locus (b); while still lighter ones, describe the locus (c) or (d). The proportion of sand carried in suspension varies with the velocity and inversely with the depth of the stream. (R. E. Hill, Proc. Am. Soc. C. E., Vol. 39, P. 263). This proportion also varies with the fineness of the grains; some being too large to be lifted from the bottom and others being so fine they will stay in suspension in still water for months and even several years.

FIG. 1

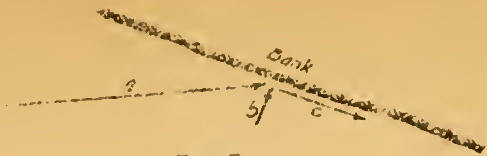

FIG. 2

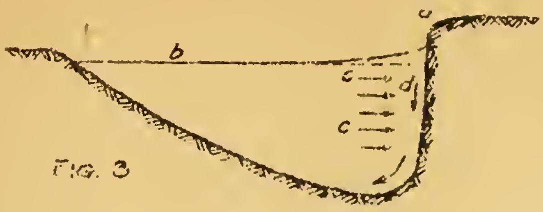

FIG. 3

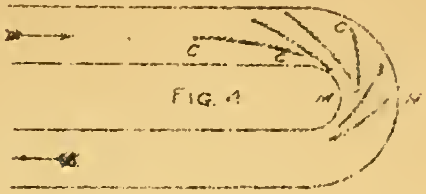

FIG. 4

FIG. 5

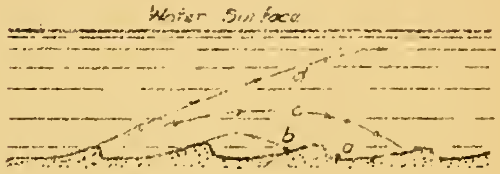

FIG. 6

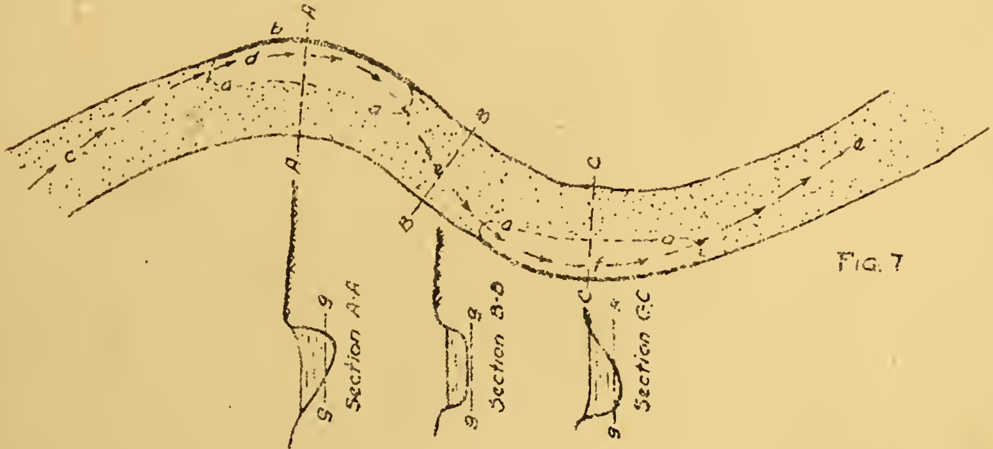

FIG. 7

FIG. 8

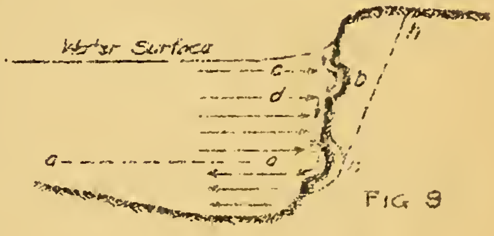

FIG. 9

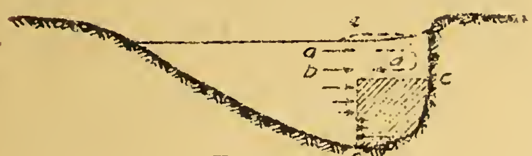

FIG. 10

FIG. 11

FIG. 12

FIG. 13

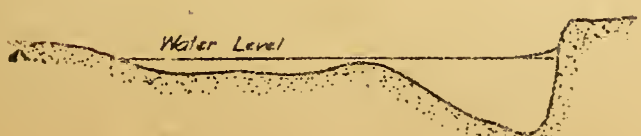

FIG. 14

FIG. 15

(Proc. Am. Soc. of C. E., Vol. 89, P. 943). It also follows that in a stream the materials of the bottom and banks are taken into suspension at the points where the velocity action is greatest and the same materials are deposited where the velocity is least.

The movement of the bank solids in the stream may be considered with respect to their detachment, their transportation and their deposition. From general observation it is well known that the solids from the banks are introduced into the stream by the erosion of the bank on the outside side of the bend of the stream as at (b, Fig. 7). The center of the flow of the swiftest part of the current on a stretch of tangent of the stream is at the center of the stream as at (c), but approaches the caving bank at (b), and at this point the channel is deepest. The swiftest part of the current then crosses over at (e) to the opposite side. At this point, known as the "cross over bar," the channel is shallower and the elevation of the bottom more uniform as illustrated by the cross section B-B. The process is then repeated from the opposite side (f) of the river. As shown by the typical cross sections, the deep bottom and the super-elevation of the upper surface of the stream swing from side to side of the channel, with a normal condition between as though one were rocking water in a pan. The contour lines (a) are at an elevation shown on the cross sections at (g). The paths of the major portion of the solids and the places of their deposition follow generally the flow of the currents nearest the wetted perimiter, as were shown in Fig. 4 and Fig. 5. These two processes are affected, however, by other influences and their exact operations still furnish themes for animated engineering discussion. It is the erosion of the bank, however, that causes the major property loss adjacent to streams. In this respect the subjects of transportation and deposition of the eroded material are of secondary importance and for the purposes of this paper will not be pursued farther; suffice it to say that the movement of the solids determines to a large extent the location, widths and depths of the stream channel.

In a uniform channel on a straight stretch of a stream there is very slight scouring. (Trautwine, 18th Edition, P. 577). Some distinct action must take place at the bend of a stream to cause the detachment of the bank material. Considering the perimiter currents as shown by Prof. Thompson to exist in the bends of streams, there is a downward velocity on the face of the steep, caving bank. Particles of solid material (Fig. 8), attached to the face of this bank have acting upon them to dislodge them and carry them downward, the downward current velocity plus gravity; across the bed of the stream they have velocity only and as they ascend the opposite side they have velocity minus gravity. As the velocity decreases the particles are finally deposited, the heavier at the lowest point of the bed of the stream and the lighter higher up and further across the bed, thus giving the gradations in size at different depths found in all old channel excavations.

It is commonly known that the erosion of a bank practically stops when the water reaches a height at which it overflows the eroding bank. When the mean surface elevation of the water in the stream rises from (a) to (a'), above the bank, assume, for the purpose of argument, that it retained its surface contour in the position (a'-b'). Since the bank resistance is re-

moved the head at (b') will be converted to velocity at (c) and the water surface will drop to practically the level (a'-a'). This assumption of a horizontal surface eliminates the downward pressure along the face of the bank and thus removes the downward current by removing its cause. The active downward force on a solid particle in the bank is reduced to gravity only and the caving becomes materially less.

Another characteristic of caving banks is that the actual scouring on the caving bank is not near the surface of the water, but is low down, undermining the material until it drops in mass. The path of the water in its motion around the bend approximates a helix. It crosses the channel on the surface, drops to the bed of the stream and recrosses the channel. With the two cross currents in the stream, one above and one below, there must be a region somewhere between these two currents where they affect each other in amount and direction, and at the center of this region a surface where the cross stream currents are neutralized and the resultant motion of the water is parallel with the center line of the channel. The neutral surface or plane is indicated in section at (a-a) Fig. 9. Consider an incipient, longitudinal cavity in the vertical bank at (b) which if increased, will undermine the bank. The downward current is assisted in entering the cavity by the pressure (c) from the current, but this action is counterbalanced by the pressure (d) below (c) and acting in the same direction. Consider again a cavity lower down and at the neutral plane (a-a). The force (f) drives the vertical current into the cavity and the force (g) below acting in the opposite direction assists in its discharge and the enlarging, undermining cavity finally causes a plane of cleavage in the bank above it; the trace of which is indicated at (h-h).

Bank Protection

Since the current causing the caving of the bank on the bend of a stream acts vertically, a horizontal obstruction is the most direct method of intercepting it. In Fig. 10 the arrows (a and b) represent the cross channel component of the helicoidal current. If an artificial bank (c-c) be placed with its top horizontal surface above the neutral plane, the downward current (d) is deflected streamward and meets the opposing current (b) with the effect that the downward current (d) is destroyed. The artificial bank has the further effect of starting a downward current on its own vertical surface with a new adjustment of forces and a new and lower neutral plane. These new conditions also cause a higher elevation of the surface of the stream at (e) farther from the bank, and a corresponding lower elevation at the bank.

This process may be continued indefinitely by increasing the number of steps in the artificial bank (Fig. 11), which, carried to the limit, is the plane at (a-a). This furnishes the first method of preventing the erosion of the concave bank in the bend of a stream by sloping back the bank to a line (b-b). This method has been quite commonly used over a long period of time with very satisfactory results. As it is impractical to extend the bank slope below the low water line, it has been common practice to sink some form of revetment to the bed of the river and up the bank to varying distances above the low water line. Such a revetment also increases the resistance of

the sloping bank, permitting it to be maintained on a steeper grade. On account of the high cost of excavating and building the revetment, it is often desirable to build the protection within the channel of the stream. This is now commonly done by placing a permeable dike or jetty in the stream. This permeable or skeleton jetty is so placed that it intercepts and retards the current flowing along the caving bank to such an extent that the detritus carried by the stream is deposited, building a bar in the deepest portion of the channel and along the face of the caving bank. The resulting cross section then assumes the general appearance of Fig. 12, with a horizontal face (a) above the neutral plane, and a surface (b) on a slope that will intercept the vertical current.

Two general methods are used in installing permeable jetties. One is to place short spur jetties at intervals along the face of the caving bank. The intervals should be such that the bar from the up-stream jetty will not terminate before the location of the next jetty below is reached. The other method is to build one long jetty from the bank just above the point where the caving commences, and extending into the stream far enough to build a bar for the length of the caving bank. The advantages of the latter method are found in wide sand bearing streams. On account of the length of the jetty, the direction of the stream is diverted by the bar which is formed and protected by the jetty. It also avoids the danger of scouring back of the jetty at the point where the jetty comes in contact with the bank.

Obstructions of various kinds are sometimes placed at intervals down the face of the vertical caving bank. These are of value as emergency measures and where used should be placed sufficiently close together to form a comparatively quiet cushion of water next the bank to hold the downward current from direct contact with the bank. Otherwise the downward current will form between the vertical obstructions and be concentrated on the upstream side of each obstruction with serious results.

Design of Permeable Jetties

Owing to the wide variation in the composition of the detritus in the beds and banks of streams, empirical methods must be used to a large extent in the design of jetties. As to strength of members and stability, however, there are certain workable limits that can be determined by engineering processes.

Strength and Stability. The forces acting to break the members or to overturn or wash out the structure have their origin in the velocity of the stream. After the maximum mean velocity has been observed, by the use of the formulae for the flow of water in open channels, the velocity head may be determined and from this head the pressure per square foot on a plane normal to the current. In determining the amount of permeability, or, better, the non-permeability (the percent the solid area of the jetty bears to the entire face of the jetty), the amount of drift that will lodge on the structure must be taken into consideration. From 60 to 75 per cent. of non-permeability including drift will build a bar quite readily in the usual type of sand bearing stream. After the external forces have thus been determined, the jetty

is readily designed by the methods used in proportioning the members of static structures.

Shore Cutting. The danger of scouring between the shore end of the jetty and the bank must be provided for in the design and installation. Scouring varies with the square of the velocity of the stream. The jetty obstructs the stream and increases the head above the jetty and if even a small opening is left in the attachment of the jetty to the bank the increased velocity through this opening will soon widen to a channel and leave the jetty and its bar as an island in the river.

Settling. In sand bottom streams, jetties that rest on the bottom will sometimes settle even to the point of destroying their usefulness. Running water is necessary, even in quicksand, to cause serious settlement. All of three methods are advisable for use to prevent settling; means to prevent running water coming in contact with the supports; location of the jetty at an angle with the current that will give the least velocity along the supports; and the use of a material with a low specific gravity in the construction of the jetty. The materials with high specific gravities, such as steel, will settle in proportion to their specific gravities and apparently without respect to the total weight of the structure.

Location. Attention should be paid in the location of jetties to the future movement of that part of the stream not affected by the installation as this movement often affects the future usefulness of the jetty.

In a typical stream of the type we have under consideration, except where affected temporarily by unusual conditions, the bends move slowly down stream. In Fig. 13 the current from a tangent stretch of river strikes the concave bank at (a), scouring the bank and deflecting the current, but the preponderance of the scour on the bank is down-stream from the outer-most point (b) of the curve and this causes a gradual movement of the bend down-stream.

Some of the points to be observed in connection with the location are:

a. The nature of the bend just above the installation, as this bend affects both the location and the length of the jetty.

b. The length of the bar formed varies inversely with the degree of curvature of the stream and directly with its velocity.

c. The installation should not be too far up-stream to be efficient; nor should it be far enough down-stream to allow cutting back of the installation.

d. In a sandy stream, material is being moved from that part of the channel adjacent to a caving bank and, conversely, material is being deposited in that part of the channel where the bank is not caving.

e. The installation should not be placed where a tributary must cut

through the bar to reach the river channel.

PRESIDENT: Professor Dawson, formerly Professor of Hydraulics at the University, now at the University of Wisconsin, had Mr. Smith's paper and has prepared a written discussion of it. Before giving that, if Mr. Jacoby is in the room we will ask him to give brief comment regarding the report of Mr. Knapp.

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THE PRESIDENT: I will now read Mr. Dawson's discussion while Mr. Smith indicates the illustrations to which the discussion refers.

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MR. SMITH: I am pleased that Professor Dawson has called attention to the scarcity of actual experiments and the prevalence of theory concerning the currents in stream flow. Professor Thompson made actual observations on miniature streams and developed the idea by theories which have been generally accepted since that time. From general observations on the streams of the Punjab, India, Mr. P. Claxton developed a theory published in the Engineering News, Vol. 99, 1927. Mr. Claxton entirely abandons the solution of Prof. Thompson and gives two reasons in proof of his position. One is that in wide shallow streams it would be impossible for the elevation of the surface of the water at the concave bank to affect the entire width of the stream. That this is true probably all admit, but that it does not prove error in the observations of Prof. Thompson will be seen by a casual examination of such locations. Fig. 14 is a section of the Cimarron River and is typical of many locations on our very wide and very shallow sand bearing streams. The caving bank at the right and the stream bed adjacent has all the characteristics found in the deep, narrow channels although the bed of the stream in the left portion of the cross section is not affected by the super-elevation.

The second reason given by Mr. Claxton is that the feeble force possible to be generated by such a super-elevation could not overcome the main current of the river. A super-elevation at a curve in the Mississippi river has been observed to be approximately one foot at a point where the river is a mile wide. The average gradient of the Mississippi river from Cairo to the Gulf is 0.327 feet per mile or about 1/3 the gradient across the stream. The observations of Professor Thompson do not indicate that the cross current overcomes the longitudinal current but that the longitudinal current is affected in direction by the cross current. That a cross stream gradient of three times the longitudinal gradient will affect the longitudinal current, is not at all inconceivable.

Mr. Claxton introduces the theory that the water becomes more and more saturated with the bank solids as it advances down the caving bank until a point of saturation is reached where the solids are deposited. He deduces from this two results: first, that the solids are deposited on the side of

the channel from which they are dislodged, and second, that such deposits obstruct and deflect the current causing the bends in the stream.

As to the first point, there is but little doubt that much of the material from a caving bank does stay on the same side of the stream and is deposited over the bar just below the caving where the water is comparatively shallow and the current comparatively slow. But that this material is the cause of the bends in streams, is not sustained by many of the phenomena to be observed.

Consider a high, straight bank that commences to cave. There is a definite point where the caving commences and another definite point where the caving ends. The increase in caving at the upper end and the decrease at the lower end are not abrupt but gradual, and of necessity the continuance of caving most at the center and least at the ends produces a concave bank and this concave bank deflects the current and causes bends in the stream. Again if the solids are deposited at the end of the caving bank due to the water being surcharged and if this is the obstruction that causes the deflection of the current the bends in the stream would have a general movement up stream; but the general movement of bends is down stream.

There are in very flat valleys instances where a bend will temporarily move up stream, but this movement is soon arrested and reversed, or the bend coming down from above meets it, with the resulting resaca or ox-bow lake. Further in such cases the amount of curvature is great making a very long concave bank which caves for the total length of curvature without depositing bars on the caving side as one would anticipate by following the saturation theory.

Professor Dawson suggests that since the water surface is higher adjacent the concave bank the water must flow upward in place of downward. This of course is the case. When the stream enters the curve the water next the concave bank flows up to the super-elevation and is held at this elevation until it leaves the curve when it flows down again. Let us consider a filament of water (a) with unit cross section striking a concave bank (Fig.15). A resistance (b) of the bank is developed. Since water transmits an equal force in all directions we get an upward force (c) but we also get an equal downward force (d). The force (c) can be measured by the static head it induces but (d) being equal can also be measured by the same head.

#2258

THEORY AND PRACTICE IN THE DESIGN OF PERMEABLE JETTIES

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Reprint from Proceedings of the Kansas Engineering Society 1931

THEORY AND PRACTICE IN THE DESIGN OF PERMEABLE JETTIES

Introduction

For centuries the rivers' caving banks have been covered with stone and brush in attempts to protect property from the encroachment of erosion. Today the river banks are still caving; brush is getting scarce; stone is expensive, and property values along the rivers are increasing. The natural result of such circumstances is the demand for a better form of bank protection, which can be designed to give consistently good and permanent results at a minimum cost. The protection of expensive roads and bridges can not be left to untrained experimenters. Recognizing this need for better protection, trained engineers have developed the permeable jetty to a point where it can be designed as an engineering structure to suit local conditions. It is the purpose of this paper to discuss the engineering problems which enter into the design of such bank protection.

Design should start with the original survey. It is intended that this paper will point out the essentials of a good jetty survey, and will indicate the factors which influence the choice of the type of jetty. Then the actual design of a permeable jetty will be discussed in detail. By "type of jetty" is meant the arrangement of whatever units form the jetty, i.e., whether in a series of short strings or in one long wing or diversion line. A "flexible jetty" will be taken to mean a permeable jetty consisting of several units connected to each other and resting on the bed or bank of the stream.

The Significance of the Survey

A mere map of the proposed jetty site does not furnish sufficient data for an intelligent engineering design of bank protection. Surveys which are to be the basis of jetty design should be technical reports of the whole situation. (Fig. 1) Obviously, a good map of the caving bank line is essential to ascertain its length and radius of curvature. The curvature (together with the width of the river) is the prime factor in determining the length of jetties to be used. (Figs. 2 and 3.)

From figure 2 it is seen that the map should show both bank lines at both high and low water, and any bars on the side opposite the caving. This is for the purpose of studying conditions across the river before any deflection of the current is attempted. A contour map with an interval of two feet is very desirable. A good map does not terminate at the upper end of the caving. Up stream from the caving there may be bends or other conditions which would vitally affect the location of the jetties. For example, an active caving bank upstream from the bank in question will sometimes work far enough downstream to cut behind the jetties in their original location. Such conditions as these should be known before attempting to locate an installation. The upper and lower ends of all caving banks within the range of the map should be carefully designated and if possible

it should be determined whether or not there has been any recent caving. The general direction of this movement of the active caving is also very important to the designer.

Another important point in the survey-report is to learn the maximum velocity of the river at flood stage. If government reports are available, these are the best source of information. Mere estimates obtained from local men are almost always too high, as few people have much experience in judging velocities within this low range. However, local men can furnish valuable information as to the quantity and size of drift which runs at high water. The investigator should check this against his own observations as to drift accumulations along the bank and on bars. The amount of drift present will greatly influence the ultimate solidity of the jetty, and the size of the drift will indicate the size of openings through the jetty. In this connection it is well to check the frequency and duration of rises in the river, as a sudden rise in a dry stream will give the effect of impact and necessitate heavy anchorage for the jetty.

Height of banks and depth of low water must be noted for the designer's use in fixing the height of the jetty. The material of banks and stream bed must also be carefully recorded. For example, sandy banks require flat slopes for stability, and a fine bed material may necessitate extra provision for the prevention of jetty settlement. It is quite important to find out whether the opposite bank or bar will scour away if attacked by a diverted current.

The sand and silt content of the stream is perhaps the most significant item to be discovered. Because the permeable jetty utilizes this sand to protect the bank (or to divert the current), it follows that the most efficient jetty is one designed to cause the maximum deposition of the available sand. Hence the relative sand content should be known before the solidity of the jetty (percent of obstruction) is decided upon. Having a good survey and report, the designing engineer is ready to select the type of jetty to be used.

Location and General Design of Diversion Jetties

The diversion jetty has several practical applications in river work. In addition to protecting banks, a diversion wing will concentrate low-water flow for various purposes; it will scour out new channels; will fill or deepen old channels, or will serve as a control of flood water. This paper will mainly be confined to the use for bank protection, but the function of the jetty in its varied applications is similar in every instance.

With few exceptions, the diversion jetty should always be located above the upstream end of the caving. If this general rule is not observed, the usual result is that the bank caves out from behind the shore end and leaves the jetty out in the stream to form an island. However, in certain locations the caving action is visibly moving in its natural downstream direction and in such a case the jetties may be located at a point where the

cessation of caving is imminent.

Because such jetties actually change the direction of the main current, a much greater spacing between lines can be used than would be the case with short spurs. A diverted current can often be held away from the caving bank for a distance downstream of two to five times the length of the jetty. This varies with the radius of stream curvature, as suggested by figures 2 and 3. If there is sufficient room within the width of the river to use the diversion type of jetty, it will be found the most economical. The economy lies in the saving of several bank connections, and in the fact that an increased jetty length results in more than a proportionate increase in the amount of current deflection.

It is well to consider the factors which make the location of a permeable jetty quite different from the location of solid jetties. The point where the jetties leave the bank may be the same in either case, but the angle which the jetties form with the bank will probably be quite different for the two kinds of jetties. Long experience has shown that either a normal or an upstream angle will produce good results with a solid jetty. (Fig. 4) The still-water pocket above such a jetty prevents the formation of high velocities along the jetty face, and protects the bank by a cushion of quiet water even at flood stage. However, a permeable jetty installed in one of these positions will prove unsatisfactory. Since part of the stream flow can now pass through the jetty, there is no still-water pocket, and the whole situation is changed. But because only part of the original flow is to pass through the jetty, it follows that the rest of the water must be disposed of in some other direction. Figure 4 (upstream) indicates where this excess head "v" might be expended. In this case, the head will usually tear out the bank connection because the path toward "b" offers the easiest relief of head (as velocity). In case the jetty is normal to the bank (Fig. 4) the paths to the ends of the jetty are not as easy as the one through the jetty, and so the excess head will relieve itself by flowing at a high velocity straight through the permeable jetty face. This results in the destruction of any protecting bar downstream, and often the jetty itself is undercut and settled by the scouring action of the swift current. It is the object of the designer to prevent the formation of these objectionably high velocities through the jetty. This can be done by maintaining a certain predetermined maximum pressure (head) upstream.

Two conditions influence the magnitude of this head above a permeable jetty: the length of the jetty, and its angle with the bank. Whenever the length of a jetty is increased, the unit pressure along its face is increased. A very short jetty would obviously impound very little excess head and so the flow of water through the jetty would be at a desirably slow velocity. However, figure 5 illustrates how increased length builds up additional pressure. The curved paths of figure 5-a represent the flow of the excess water as it seeks to escape around the jetty end. Section 1 could probably discharge its excess around the end of the jetty and would impound no appreciable head. But sections 2, 3 and 4 are also throwing excess water to the end of the jetty so that a piling-up effect occurs all along the jetty face. The magnitudes of the "n" or pressure

components in figure 5-a increase with the length of the jetty, but at a slower rate. Hence the designer must realize that while a hundred-foot jetty may produce desirable silting velocities below it, a similar jetty twice that long will not give the same results without special design.

The other condition governing the pressure or head above a jetty is the angle which the jetty forms with the bank. Figures 6-a and 6-b show one jetty normal to the bank and the other pointed in a downstream direction. In either case, the original current "c" may be thought of as being resolved into two components as it nears the jetty. One of these is a head "n" (against the jetty) which expends itself as velocity through the jetty. The other component is a velocity "v" parallel to the jetty. If "n" (representing velocity through the jetty) is to be held to a predetermined maximum value, the other component must be made relatively larger to compensate. Figure 6-a shows a large unit-pressure "n" because very little of the original current "c" can escape around the end as velocity "v". On the other hand, in figure 6-b, the value of "n_2" is less than that of "n_1" because the component "v" can easily escape downstream and thereby reduce the pressure "n" against the jetty. The flatter the angle "j" (Fig. 8), the smaller will be the pressure on the jetty face.

Theoretically, the designer can control this velocity through the jetty by the proper design of both length and angle with the bank. In actual practice, however, the length is fixed by circumstances other than the consideration of a desirable velocity through the jetty. Hence the designer is compelled to take a given length of jetty and set it at an angle which will produce the desired retardation. In figure 7-a, "R" is the resultant of the various curved paths of figure 5-a. This resultant will produce a certain pressure value "n" which will in turn result in a certain velocity through the jetty. But assume that the outer end of the jetty is turned downstream, and it will be seen that the component "n" is reduced. (Fig. 7-b). Thus the effect of turning the jetty end is to reduce the velocity through the jetty as would be the case if the jetty were actually shortened. If the pressure "n" is still too high, sections 3, 2, and even section 1, may be bent downstream to give a final curved jetty as in figure 8. The pressure along this jetty has thus been reduced to a predetermined value even though the length could not be changed. It follows that any length of jetty may have this predetermined pressure on it if the jetty is built on this curve.

A parabola answers the requirements of the curve, viz., that both ordinates must increase simultaneously, and that the rate of curvature must not be uniform. Experience has shown that the parabola which gives the best practical curve for the jetty, has the impirical equation, $y^2 = 4000x$, where both variables are expressed in feet. . . . (Equation 1)

The foregoing equation should be modified for long jetties on narrow streams with high velocities, i.e., where the jetty obstructs a large percentage of the channel width. In such a case, the jetty acts as a partial dam and is subjected to an excessive pressure because the water cannot readily flow around the end of the jetty even though the curve is used. To

relieve this condition, the entire jetty-curve must be rotated in a down-stream direction, decreasing angle "j" of figure 8. For original stream velocities of more than three miles per hour, the following impirical formula is useful in finding the angle between the tangent and the bank:

j = 35 degrees + (arc cosecant 1/2 velocity in miles per hour) . . . .(Equation 2)

A study of the relationships indicated shows that an increased velocity will require a flatter angle. This is, of course, to provide the velocity along the face of the jetty with an easier escapement and to prevent piling up as head above the jetty.

In connection with the location of a flexible jetty, it should be noted that to locate the outer end at a higher elevation than that of the center of the jetty is often disastrous. Such procedure causes a head to pile up at the end of the jetty and results in an increased flow over and through the center of the jetty. This increased flow scours out the center, settles the units, and ruins the entire installation. The practice of extending a jetty completely across a main channel should be avoided.

When the length and direction have been determined, the height of the jetty must be considered. Ordinary circumstances demand that the bar which is formed shall be high enough to cover the toe of the caving bank. If this requirement is to be met, the jetty top should extend to at least above low water to insure a bar of sufficient height. Rarely does a jetty form a bar as high or higher than the jetty itself. When flood waters are to be controlled, the height must be increased. If ice is known to form in the river, the jetty should be as low as possible to permit ice-floes to pass over the top.

Location and General Design of Spur Jetties

Spur jetties, as the name would indicate, are short jetties extending into low water and at least part way up the bank. The entire length of the caving area must be covered if this type of protection is selected. Spur jetties are usually the designer's choice where there is no room to divert the current toward the opposite bank. The function of such jetties is to catch as much drift as possible, and thus to retard the flood flow along the bank. Large bars are not to be expected, as the field of action is limited and protection is afforded by retarding the current to below the scouring point. Spurs serve very well in places where the shape of the bank line must not be disturbed, such as a stretch of railroad right-of-way where the caving is in the incipient stage.

Because the spur jetty does not attempt to divert the current it is continually subjected to heavy pressure from the intermittent rises, and this without any appreciable assistance from bars below the jetty. For this reason, particular attention must be given to the strength of members and to anchorage. Heavy runs of drift at flood season tend to push the spurs out of line, so that they become parallel to the bank where they are of little

effect. To obviate this tendency, all lines should be fastened together at least at their outer ends. Special anchorage must be provided for the first or upper line. This may be to a point in the stream bed or to the bank if the anchor is far enough upstream. The significance of this statement is readily seen if the jetty, the upper anchorage, and the current be taken as three forces in equilibrium. Since the jetty and the anchor-cables may be thought of as tension members, the third member (current) must be in compression and lie between the other members. From this it is seen that a short upper anchorage to the bank can not prevent the jetty from swinging into the bank under the pressure of the current (compression member).

The correct spacing and length of spurs may as yet be mainly a matter of observation and engineering judgment, but two well-defined rules must govern such judgment. These two rules are: 1. Space spur lines close enough to insure the formation of a continuous bar or still-water area along the entire toe of the caving bank. 2. Extend the spurs far enough up the bank to prevent flood water from cutting behind the bank end of the jetty. While these rules appear to be rather elementary, many spur installations have proved inefficient only because the builder neglected the design of spacing and length. On stretches of tangent, a spacing of twice the length of the jetty may be justifiable. A short radius curve will often require a spacing of less than the jetty length. Average practice is to space the lines about as far apart as the length of the line. The result of too wide a spacing is the continued or even augmented caving by eddies between the lines. It must be remembered that stability of the toe is the key to the protection of the caving bank, and if any points along the toe are left unprotected by a cushion of water or sand, the bank will be undermined and continue in its steep, caving profile. As soon as the toe is stabl , the upper bank begins to weather to its angle of repose so that vegetation will again grow on the slope.

The length of a spur jetty, as suggested in rule two, must be such that high water can not cut a channel around the bank end. It is equally important to extend the outer end into low water and beyond the toe of the slope. Jetties installed to cover only the bank slope are doomed to failure for they provide no protection at the toe. A low velocity does not necessitate as long a spur as do higher velocities. This is obvious, for it is easily observed that even a very short spur will effect a retardation of the current over a considerable stretch of bank if the current is not very swift.

If the bank is higher than the flood stage of the river, it may not be necessary to protect to the top of the bank, but only to the high-water mark. However, good practice usually requires that the jetty be extended at least to the top of the bank and often several feet back onto level ground. The latter case will be considered under the "Design of Bank Connections."

It is difficult to attempt any formula for the height of jetty-units. Experience seems to indicate that a variation in height in this type of jetty does not materially affect the usefulness. It is better, however, to decrease the spacing between lines to correspond to any decrease in height below six feet.

Combination Arrangements of Various Types of Jetties

Certain situations call for a modified or combined form of the diversion and spur jetties. For example, it may become necessary to set a diversion jetty at a rather large angle with the bank with the result that cutting at the bank is feared. A few spurs placed above the main jetty will reduce the velocity of approach to below the danger point. Again, on a curving bank followed downstream by a tangent, a diversion line will probably be best for the curve, while the tangent should be protected by spurs. (See Fig. 9.) The dotted lines touching the outer end of the jetties show the smooth bank line which should eventually be formed. This is desirable, for an uneven bank line (though covered by jetties) offers excessive interference to the naturally straight flow and tends to start caving by creating whirls and eddies.

Banks of a stiff material which slips and slides in considerable quantities offer a problem different from the ordinary. Figure 10 shows a solution. As the bank "b" slips into the stream, the jetty "p" parallel to the bank intercepts the earth and holds it at the toe of the slope. If cables are used longitudinally in this jetty, they must be several times as large as if designed for simple water pressure discussed later. The amount of earth intercepted and held by the jetty is rather indefinite, but is sometimes enormous so that a large factor of safety should be allowed. The spurs "n" tie the main jetty "p" to the bank and prevent high water from cutting behind the jetty. It is absolutely essential to make use of these spurs on a training jetty. Special cases such as this require some study, but involve only slightly different details than those already discussed.

A common supplement to a diversion installation, is a newly excavated channel through which it is desired to divert the entire stream flow. (Fig. 11) It is not within the scope of this paper to discuss diversion channels at any great length, but their relation to jetties is often quite important to the designer of the jetty. Whenever possible, the new channel should be located with its upstream end at the point of caving, or at least above the cross-over bar where the thread of the stream starts to the opposite bank. The function of the jetty in such cases is to silt up the old channel and to create an excess head which will induce a flow through the new channel. For this reason, jetty and channel should be built about parallel. If the created head is to be of any effect, the jetty must not be too far downstream. The lowest desirable limit of the jetty location is about the downstream edge of the new channel. It is not often advisable to curve the new channel, as caving will proceed rapidly at the bends and change the direction of flow. It is, however, a good plan to have the upper end of the new channel a trifle widened to make certain that a large volume of flood water will be carried and that consequent scouring will enlarge the channel to the desired proportions.

Design of Solidity

Solidity of a jetty may be expressed as the ratio of the solid parts of the jetty to the total area of the jetty face, measured in the same verti-

cal plane of projection. It is obvious that with free escapement around the end of the jetty, the amount and velocity of water passing through the jetty will decrease if the jetty face is made more solid. Hence if the same kind of jetty is to be used in various locations, the jetty should be such as to permit the control of solidity so as to suit the various velocities. Patented steel jetties have an original solidity of from 10% to 20%. The additions of poles or brush will increase these figures, but the result is only temporary, as these materials quickly rot away.

Accumulations of leaves and drift will stop up the jetty openings and give the effect of increased obstruction to the current. If this drift can be depended upon to stay on the jetty, it usually serves a good purpose. Small drift produces the best results, for it becomes entangled in the jetty and does not float off during high water. To catch small drift requires the use of smaller openings through the jetty. Experience shows that about eight square inches is a good size for openings provided the openings are not too narrow. Larger openings fail to catch much of the smaller drift which on some western streams is the only drift available. These dimensions for openings are only average values and can not be used in every instance. As will be noted later, the use of wire mesh (or other means to provide small openings) necessitates a heavier jetty to maintain stability under the increased pressure which occurs when the wire mesh solidifies.

In the case of a flexible deflection jetty the first high rise in the river often gives the most severe test. This happens when the jetty has not had sufficient time to build a bar which would assist in resisting the pressure. Thus it is seen to be advisable to provide the jetty with some means of utilizing the small drift and silt which is present at even low water stages. Here again pole or wire mesh answers the purpose if, as mentioned previously, the jetty is built sufficiently stable.

To obtain a desirable uniform protecting bar, a uniform obstruction should be presented to the current. Of course a very slight obstruction produces some retardation, but a jetty with wide open gaps usually forms a series of small bars with channels in between. The increased velocities through these channels soon scour away what bars have formed. On the other hand, a uniform obstruction results in a uniform velocity through the jetty and eventually the formation of a solid bar below the jetty, insuring protection to the banks.

Perhaps it is obvious that very clear streams require jetties which offer a relatively high percentage of obstruction, but a designer may easily err in the other direction when the stream carries heavy burdens of silt and small drift. Excessive small drift may completely fill the openings through a jetty, causing water to pour over the top of the units as if they were a dam. This action washes out any bar below the jetty and the purpose of the structure is partially defeated. To overcome this difficulty, it is possible to design the uppermost openings larger than those lower in the jetty. Such an arrangement does not disturb the uniformity of obstruction (considered longitudinally along the jetty face). Uniformity of obstruction in that direction should always be maintained.

Without more accurate experiments, few designers would specify the exact size of openings required for a given velocity and silt content. Too often the kind of jetty selected precludes the adjustment of solidity to suit the location. At least, the designer can ascertain whether the drift to be expected is small, such as Russian thistles, or whether it may be trees of a considerable size. He can also know whether it requires long periods to build up bars or if deposits form rapidly. The knowledge of these very general conditions should assist the designer in fixing the original solidity of any jetty which may be selected.

Design of Anchorage

This section has to do particularly with the anchorage of flexible jetties (not attached to the stream bed), cabled to deadmen or anchors upstream. The general principles here used are applicable to pile-jetties, but the desired result in that case is to find the stress in a pile-beam. In a flexible jetty the result sought is the stress in the anchor-cable. The maximum unit-pressure on the jetty must first be found. Because the jetty is permeable, it is not subjected to any appreciable hydrostatic pressure, and any other pressure must result from velocity head:

$$\left(h = \frac{V^2}{2g}\right) \quad \ldots\ldots\ldots\ldots \quad \text{(Equation 3)}$$

Solving this equation, we find the head "h," in feet, which, multiplied by the unit weight of water, gives the unit-pressure on the jetty due to velocity. Such a unit-pressure must be modified by two factors: the angle of the jetty with the current, and the degree of solidity. Combining all the terms, the resultant pressure per square foot of jetty face equals

$$\frac{(\text{Maximum velocity})^2}{2 \times 32.2} \times 62.5 \text{ lbs.} \times \text{sin angle between jetty and current} \times \text{percent solid} \quad \ldots\ldots \quad \text{(Equation 4)}$$

Each cable must carry a stress equal to the preceding product times

$$\frac{\text{Area of jetty between successive jetty anchor-cables}}{(\text{Sin angle between jetty and cables})} \quad \ldots\ldots \quad \text{(Equation 5)}$$

In case the jetty units are heavy enough to resist a limited amount of overturning force, such resistance may be deducted from the cable-stress. A simple moment equation about the lower edge of the jetty will suffice to solve for this resistance. A factor of safety should be allowed to provide for variation in maximum velocities, for possible faulty cable, and for ice-floes (if this latter be advisable). If these items be considered, the ultimate strength of the cable should be used instead of the working strength.

The efficacy of deadmen has long been appreciated. Jetties seldom fail by reason of new deadmen breaking. Failure does occur either by reason of the bank caving out behind the deadmen or by rotting if logs are used. Simple remedies for these two difficulties are: 1. Longer anchorage into stable soil. 2. The use of concrete or other permanent materials. Anchors which are placed in the stream-bed may be piling, concrete blocks or steel anchors. Where gradual settling of the anchor is depended upon for

future anchorage, the designer must assure himself that underlying rock is far enough below the stream bed to permit sufficient settling of the anchor. Here, again, it is well to remember the axiom stated in the section on "Location of Spur Jetties," which says that the direction of river and bank cables should be such that equilibrium is maintained between cables and current.

Design of Bank Connection

The function of the connection at the bank is to prevent both floods and low water from cutting behind the jetty. Experience shows that to make this connection of a temporary nature is a serious mistake. Through the entire life of the jetty the bank connection is subjected to attack by the current and hence the connection should be as permanent as the rest of the jetty. If caving exists at the point of connection, the jetty should extend back onto stable soil, in anticipation of further caving.

The height, shape and material of the connection are not as important as is its flexibility. If a connection is fixed rigidly and can not adjust itself to changing conditions, the whole jetty will fail. For example, if wire mesh is used, the designer should use a wide apron which can fill any voids that may occur. If steel units are used, the attachment to bank cables should be near the bottom of the unit to permit its settlement into voids. Even brush should not be cabled so as to leave it suspended above the bed if a hole should scour underneath it. Probably the most dangerous point of scour is at the edge of low water. Here the scour undermines the entire bank and great care must be given to the design of this part of the connection.

A shorter bank connection may safely be used if the bank is sloped before installing the jetty. Weathering will eventually produce a sloped bank of $1\frac{1}{2}$:1 or flatter, if the toe is protected, but if artificial sloping is done at the time of installation, stability is hastened and there is less need to provide for future caving at the connection. The probable severity of current attack may be judged somewhat by the angle at which the current strikes the bank, and by the velocity. An increase in either of these factors necessitates increased care in the design and installation.

As was previously pointed out, the flexible deflection jetty induces a secondary current (parallel to the jetty face) which is quite likely to scour beneath and settle the units. Two methods have been successfully used to prevent this settling action. The first method is to use a jetty material having a low specific gravity. Even the novice knows that the relative tendency of bodies to sink in water is a function of their specific gravities. The popular statement of this fact may be in somewhat different terms, but the relative buoyant effect of the lower specific gravity is the principle suggested in any case. Since the settling of jetties occurs in semi-liquid sand, this same principle is applicable. An example of two common jetty materials is seen in the case of concrete and steel. Taking the respective specific gravities as 2.4 and 7.8, the submerged weights of equal volumes of concrete and steel are in the ratio of 1:4.8.

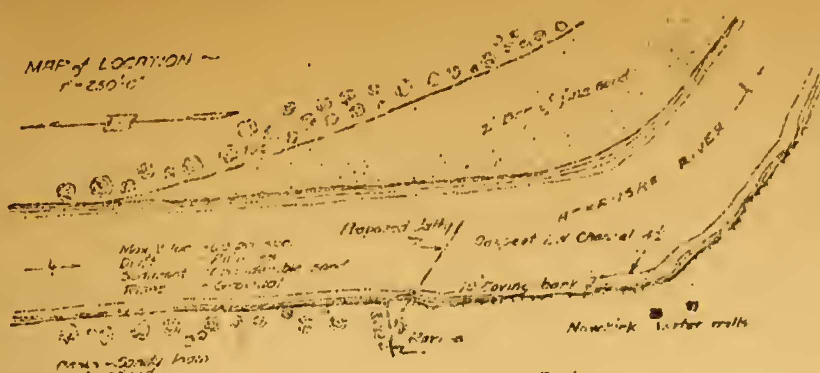

FIG 1

FIG 2

FIG 3

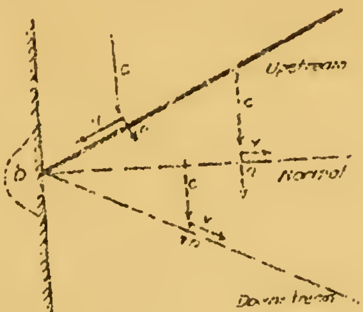

FIG 4

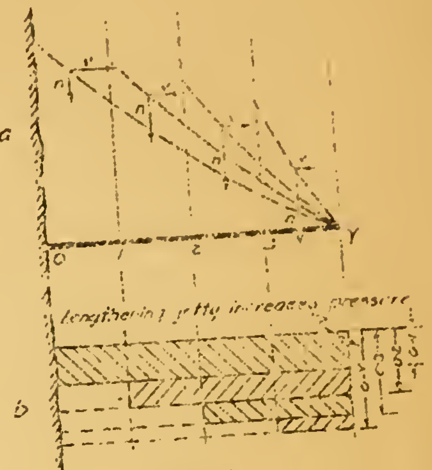

FIG 5

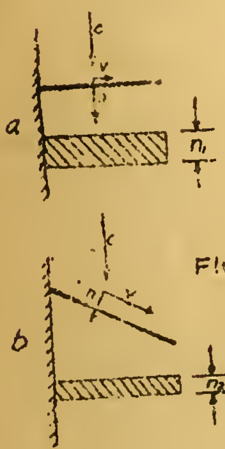

FIG. 6

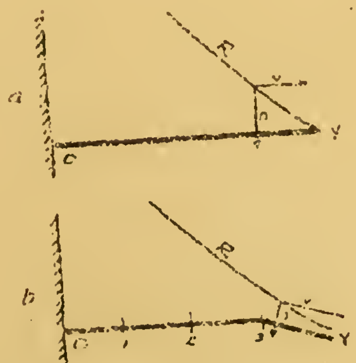

FIG. 7

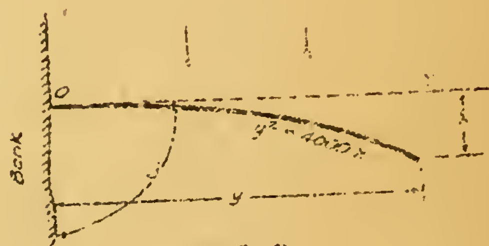

FIG. 8

FIG. 9

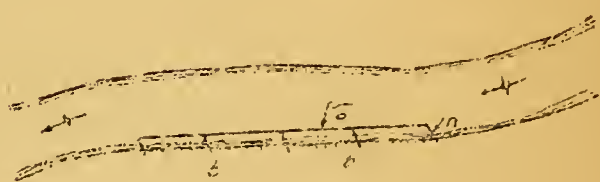

FIG. 10

FIG 11

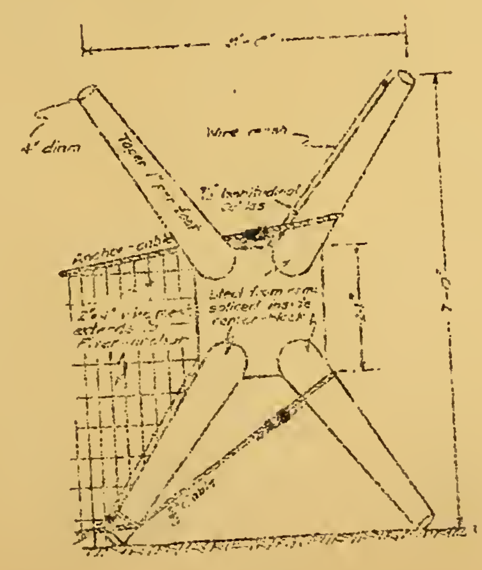

FIG 12

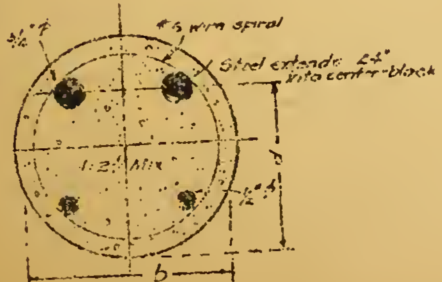

FIG. 13

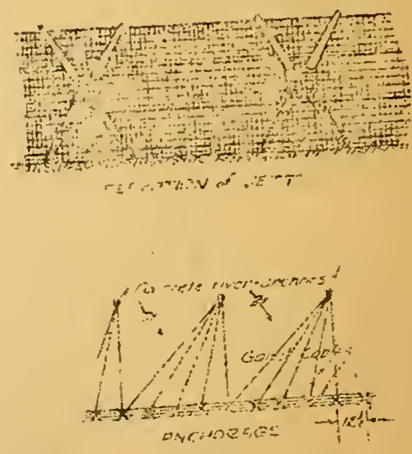

FIG. 14

This clearly shows the advantage of selecting jetty material having a low specific gravity, if settling is a consideration.

The second method of preventing scour and subsequent settling is to hold the induced current away from the jetty face. This has been accomplished by the use of secondary jetties normal to the main jetty and connected to it. These short spurs running upstream from the deflection jetty intercept the induced current as it flows parallel to the deflection line. Bars are thus formed above the upstream face of the jetty so that the current is held away and prevented from scouring at a point where settlement of the jetty would be the result. These same small bars act as a cushion against ice-floes.

Example of Bank Protection Design

Figure 1 represents an actual problem in bank protection. Details of the engineers' design are given as an example of the general procedure in such work.

Location

It will be seen that the city's wells were endangered by erosion of the adjacent river bank; hence the problem was to check the erosion from its upper end to a point just below the wells. Erosion farther downstream was of no immediate interest to the city. Smith concrete jetties were selected for the installation. Because of the low sandbar across the river and the fact that the caving bank was but slightly curved, it was decided to effect the deflection of the current by one diversion wing. Erosion extended about 800 feet above the wells, so a 300-foot jetty was located just below the small ravine at the upper end of the caving.

Height and Bank Connection

At low stages the water was only about 4 feet deep; consequently 7-foot units were used. This height was sufficient to insure the formation of a sand bar high enough to cover the toe of the caving bank below the jetty. The deep channel at the bank required a few $8\frac{1}{2}$-foot units to bring the tops of all the river units to a fairly even grade. It seemed likely that some little caving might continue above the jetty for a short time and for this reason three units were placed on top of the stable bank at $12\frac{1}{2}$-foot centers to provide for such an emergency.

Curvature and Water Pressure

Applying the formula $y^2 = 4000x$, the offset of the outer unit from the tangent O-Y was found to be $22\frac{1}{2}$ feet. (Equation 1 with $y = 300$ feet.) Also solving for the angle "j" (fig. 6 and equation 2) "j" was found to be 35 degrees + (arc cosecant 1/2 x 6) = 35 + $19\frac{1}{2}$ degrees = approximately 55 degrees.

Unit-pressure on the jetty =

$$\frac{(8.8 \times 8.8)}{2 \times 32.2} \times 62.5 \text{ lbs.} \times \sin 60 \text{ degrees} \times 50\% = 32.5 \text{ lbs.} \quad . \ . \ . \text{ (Equation 4)}$$

Fifty percent ultimate solidity was used because wire mesh with 2" x 4" openings was to extend over the entire jetty and would collect considerable small drift, thus increasing the original solidity of 18% to approximately 50%.

Anchor Cables

Concrete river-anchors were to be settled into the stream bed 50 feet apart and 50 feet upstream from the jetty (fig. 14). Thus the maximum cable stress would occur in those cables making the smallest angle with the jetty line (here 45 degrees).

Maximum cable stress (8½-foot units) $= \dfrac{12\frac{1}{2} \times 8.5 \times 32.5 \text{ lbs.}}{\text{Sin } 45 \text{ degrees}} = 4880$ lbs. . . . . (Equation 5)

From this amount was subtracted 1000 lbs. as the assumed overturning resistance for each unit. This amount (1000 lbs.) was later checked and found correct. 4880 lbs.-1000 lbs. = 3880 lbs. Using a factor of safety of 2.0, the required strength for each anchor-cable was 7760 lbs. An 8500-lb. 1/2-inch cable was selected. Four 3/8-inch longitudinal cables running between the units were used to support the wire mesh. The total ultimate strength of these cables was 20,000 lbs.

Jetty Unit

The general form of the Smith concrete jetty unit is shown in figure 12. The central mass of concrete serves chiefly to bond the diverging arms at the center, although the additional weight is desirable. Hence the design of the unit consisted in calculating the strength of the cantilever arms and checking that strength against the maximum pressure brought to the arms through the cables and wire mesh. Figure 13 shows the arm section adopted for the 7-foot units. A taper of one inch per foot was found to give a section strength proportional to the stress from the bending moment at the given section, using a concentrated load. Below are given data and calculations of the arm strength (taken as a reinforced concrete cantilever beam). Because of the nature of the structure, the ultimate strength of concrete and the elastic limit of steel were used for f^c and f^s respectively. Even the partial failure of a jetty member is not serious enough to justify the added expense of using standard working stresses for f^c and f^s:

Arm Strength

$A_s = 2 \times 0.44 = 0.88$ sq.in. $\qquad f^c = 2,500$ lbs.

$d = 5.65"$) (Figure 13) $\qquad f^s = 50,000$ lbs.

$b = 7.10"$) $\qquad n = 15$

$k = \sqrt{2pn + p^2n^2} - pn = 0.545$

$j = 0.818$

Moment arm = 48" = length of jetty arm.

Moment = 48" x W $\qquad W = \dfrac{\text{Moment}}{48"}$

$$W^c = \frac{\frac{1}{2}f^c \times j \times k \times bd^2}{48"} = \frac{\frac{1}{2} \times 2500 \times 0.818 \times 0.545 \times 226.5}{48"} = 2629 \text{ lbs.}$$

$$W_s = \frac{p \times f^s \times j \times bd^2}{48''} = \frac{0.0219 \times 30{,}000 \times 0.818 \times 226.5}{48''} = 2545 \text{ lbs.}$$

Maximum pressure carried by one arm = 1/4 total area between units multiplied by unit pressure on jetty = $\frac{7 \times 12\frac{1}{2}}{4} \times 32.5$ lbs. = 712 lbs.

$\frac{2545}{712}$ = factor of safety = 3.5+

(Design for arm strength thus proved correct)

Bond in Center Block

Maximum steel stress	= 2 x 0.44 x 30,000 lbs.	= 26,400 lbs.
Bonded area	= 2 x 24" x 2.36"	= 113.28 sq.in.
Unit bond stress	= $\frac{26{,}400}{113.28}$	= 233 lbs. per sq. in.

Resistance of Unit to Overturning

Gross weight of unit . . . . .1888 lbs.
Submerged wt. (sp. gr. concrete = 2.4) . . . . .1105 lbs.
Weight of unit acts through center line of unit.
Overturning force acts through 1/3 point (from bottom).
X = overturning force.
Moment equation about lower downstream arm is

(7/3)' x X lbs. = 1105 lbs. x $2\frac{1}{2}$', "X" = 1185 lbs.

(Assumption of 1000 lbs. was on side of safety)

Figure 14 shows some of the details of the completely designed units. This installation has now been in service for about three years, and all calculations as to strength, stability, and solidity have proved to be correct. The bar on the opposite side of the river is being cut away and a large sandbar extends from the jetty to a point below the wells, giving complete protection to this property.